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Total Maximum Daily Load for Total Dissolved Gas in the Mid-Columbia River and Lake Roosevelt

Washington State Department of Ecology

Spokane Tribe of Indians

U. S. Environmental Protection Agency

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and the Washington State Department of Ecology
in cooperation with the Spokane Tribe of Indians

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For a printed copy or a compact disk of this publication, contact:

Helen Rueda
U.S. EPA
811 SW Sixth Avenue
Portland, OR 97204

Phone: (503) 326-3280
E-mail: rueda.helen@epa.gov

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For a printed copy of this publication, contact:

Jean Witt
Department of Ecology Publications Distributions
PO Box 47600
Olympia WA 98504-7600

Phone: (360) 407-7472
E-mail: ecypub@ecy.wa.gov

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by
Paul J. Pickett[1]
Helen Rueda[2]
and
Mike Herold[3]

[1]Washington State Department of Ecology
Environmental Assessment Program
Olympia, WA 98504-7710

[2]U.S. Environmental Protection Agency
Oregon Operations Office
Portland, OR 97204

[3]Washington State Department of Ecology
Water Quality Program
Olympia, WA 98504-7600

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Acronyms and Abbreviations

Corps	U.S. Army Corps of Engineers
CRITFC	Columbia River Inter-Tribal Fish Commission
DGAS	Dissolved Gas Abatement Study
EPA	U.S. Environmental Protection Agency
FERC	Federal Energy Regulatory Commission
FMS	Fixed Monitoring Station
fmsl	feet above mean sea level
kcfs	thousand cubic feet per second
mm Hg	Millimeters of Mercury
MOA	Memorandum of Agreement
NMFS	National Marine Fisheries Service
NPDES	National Pollutant Discharge Elimination System
TDG	Total Dissolved Gas
TMDL	Total Maximum Daily Load
WAC	Washington Administrative Code
WBID	Waterbody Identification
WRIA	Water Resource Inventory Area
303(d)	Section 303(d) of the federal Clean Water Act
7Q10	Seven-day, ten-year frequency flow
ΔP	Excess gas pressure over barometric pressure

Abstract

This Total Maximum Daily Load (TMDL) addresses total dissolved gas (TDG) in the mainstem Columbia River from the international border with Canada to its confluence with the Snake River. The state of Washington has listed this area on its federal Clean Water Act 303(d) list due to TDG levels exceeding state water quality standards. EPA is issuing the TMDL for all waters above Grand Coulee Dam, and for all tribal waters. Washington State is issuing the TMDL for state waters below Grand Coulee Dam and submitting it for EPA's approval.

Elevated TDG levels are caused by spill events at seven dams on the Mid-Columbia River and other dams upstream of the international border and in the Spokane River. Water plunging from a spill generates TDG at high levels, which can cause "gas bubble trauma" in fish. Spills are provided to meet juvenile fish passage goals, and can also be caused by lack of powerhouse capacity for river flows (involuntary spills) which can result from turbine maintenance or break-down, lack of power load demand, or high river flows.

This TMDL sets a TDG loading capacity for the Mid-Columbia River, both in terms of percent saturation for fish passage and excess pressure above ambient for non-fish passage. Allocations are specified for each dam and for upstream boundaries. Attainment of allocations will be assessed at monitoring sites in each dam's forebay and tailrace, excluding the area below the spillway downstream to the end of the aerated zone, as well as at the upstream boundaries.

A Summary Implementation Strategy prepared by Ecology and the Spokane Tribe describes the measures that will be used to meet allocations. Short-term actions will primarily focus on meeting requirements of the Endangered Species Act while long-term goals will address both Endangered Species Act and TMDL requirements.

Acknowledgements

The U.S Environmental Protection Agency and the Washington State Department of Ecology wishes to acknowledge the cooperation of the following agencies in the production of this TMDL.

- The Spokane Tribe of Indians provided limnology data that their scientists have been collecting in Lake Roosevelt. The Tribe also provided review and technical input throughout the TMDL process, and assisted in implementation planning for Lake Roosevelt in conjunction with Ecology.

- The Confederated Tribes of the Colville Reservation provided comments and technical input.

- The U.S. Army Corps of Engineers (Seattle District, Walla Walla District, and Northwest Division) provided extensive technical information for this TMDL. This TMDL would have been much more difficult without the understanding of total dissolved gas production resulting from the DGAS study.

- NOAA Fisheries provided valuable advice and review. The Biological Opinion issued in December 2000 pursuant to the Endangered Species Act was invaluable in describing the studies that have been conducted to date, and in specifying the effects of total dissolved gas on fish.

- Staff from the Kootenai, Nez Perce, and Kalispel Tribes also contributed to the process.

- The Bonneville Power Administration, U.S. Bureau of Reclamation, and Douglas, Chelan and Grant County Public Utilities Districts, Teck Cominco, Seattle City Power and Light, Avista, BC Hydro, Golder Engineers, Aspen Sciences, Aquila, the BC Ministry of Water, Land and Air Protection, Columbia River Integrated Environmental Monitoring Program (CRIEMP), and Environment Canada provided technical input and assistance.

Nothing in this TMDL purports to represent the technical or policy positions of any of the above agencies or organizations. Any flaws in this TMDL are entirely the responsibility of the U.S. Environmental Protection Agency and the Washington State Department of Ecology.

Executive Summary

Description of Waterbody, Pollutant of Concern, and Pollutant Sources

This Total Maximum Daily Load (TMDL) addresses total dissolved gas (TDG) in the mainstem Columbia River from the international border with Canada to its confluence with the Snake River. This section of the Columbia River includes waters of Washington State, the Colville Tribe and the Spokane Tribe. Washington State has listed multiple reaches of the Mid-Columbia River and Lake Franklin D. Roosevelt (Lake Roosevelt) on its federal Clean Water Act 303(d) lists due to TDG levels exceeding state water quality standards. The entire reach is considered impaired for TDG. EPA is issuing the TMDL for both state and tribal waters above Grand Coulee Dam including all of Lake Roosevelt to the high water mark. EPA is also issuing the TMDL for tribal waters below Grand Coulee Dam. Washington State is issuing the TMDL for state waters below Grand Coulee Dam and submitting it to the U.S. Environmental Protection Agency for its approval.

TDG studies in the Mid-Columbia River (above the Snake River), Lake Roosevelt, the Spokane and the Pend Oreille rivers, and in Canada were reviewed for information to support the development of a TDG TMDL report. The particular focus is on studies that collected TDG data and characterized the generation of TDG by the Mid-Columbia dams and from sources that effect TDG levels in Lake Roosevelt.

Elevated TDG levels are caused by spill events at seven hydroelectric projects on the Mid-Columbia River and at hydroelectric projects upstream of the Columbia River's international border crossing. Water spilled over the spillway of a dam entrains air bubbles. When these are carried to depth in the dam's stilling basin, the higher hydrostatic pressure forces air from the bubbles into solution. The result is water supersaturated with dissolved nitrogen, oxygen, and the other constituents of air. Fish in this water may not display signs of difficulty if the higher water pressures at depth offset high TDG pressure passing through the gills into the blood stream. However, if the fish inhabit supersaturated water for extended periods, or rise in the water column to a lower water pressure at shallower depths, TDG may come out of solution within the fish, forming bubbles in their body tissues. This gives rise to gas bubble trauma, which can be lethal at high levels, or give rise to chronic impairment at lower levels. There is extensive research reported in the literature on the forms of physical damage to fish that represent the symptoms of gas bubble trauma.

Spills can occur at any time for several reasons:

- Fish passage spills (voluntary spills), conducted under the Biological Opinion in compliance with the federal Endangered Species Act.
- Spills required when flow exceeds powerhouse capacity (involuntary spills).

There are three main reasons for involuntary spills:

- The powerhouse cannot pass flood flows.
- The powerhouse is off-line due to lack of power demand.
- The powerhouse is off-line for maintenance or repair.

The six dams below Grand Coulee Dam on the Mid-Columbia are run-of-the-river dams with very little storage capacity. Therefore, spills are often forced due to operational decisions at Grand Coulee Dam.

This document describes the production of TDG at the seven projects in the Mid-Columbia River and the sources of TDG impairment affecting Lake Roosevelt. It presents general production equations representing the production of TDG, and specific equations taking into account each project's particular physical characteristics for sources within the TMDL scope area. Other sources of TDG in the TMDL area, such as tributaries, are also considered. TDG is also affected by barometric pressure and water temperature, and these influences are addressed in the TMDL.

Description of the Applicable Water Quality Standards and Numeric Target

The water quality standards for Washington State, the Colville Tribe and the Spokane Tribe have an identical TDG criterion: *110 percent of saturation not to be exceeded at any point of measurement.* This criterion does not apply to flows above the seven-day, ten-year frequency flow (7Q10) flood flow for the Washington State and Colville Tribe standard. In addition, special limits for TDG are established as a special condition in Washington rules, to allow higher criteria with specific averaging periods during periods of spill for fish passage. Neither tribal standard allows higher TDG for fish passage spills. This TMDL addresses only the 110% criterion in waters shared with the tribe and waters upstream of tribal waters.

Loading Capacity

Loading capacity for TDG under non-fish passage conditions has been defined in terms of excess pressure over barometric pressure (ΔP). This parameter was chosen because it can be directly linked to the physical processes by which spills generate high TDG, and it has a simple mathematical relationship to TDG percent saturation. Loading capacities ranging from 72 to 75 mm Hg have been set for four reaches of the Mid-Columbia and Lake Roosevelt in the TMDL. These capacities are calculated to meet 110% saturation during critically low barometric pressure conditions.

Loading Capacity during fish passage conditions is directly based on the fish passage TDG criteria for the forebay and tailrace of each dam.

Pollutant Allocations

Because of the unique nature of TDG, load allocations are not directly expressed in terms of mass loading. Like loading capacity, load allocations for non-fish passage will be made in terms of ΔP defined site-specifically for each dam, while load allocations for fish passage are made directly in terms of TDG percent saturation. A load allocation is also specified for the upstream boundary of the TMDL area and the Spokane River. The waste load allocation under this TMDL is zero, because no NPDES-permitted sources produce TDG.

Long-term attainment of load allocations for dam spills will be assessed at the downstream end of the aerated zone below each spillway. Distances are specified for the monitoring location at each dam. As a result, attainment of the load allocation will be assessed in the spill from each dam individually at a specified monitoring location, with allowance made for degassing in the tailrace below the spillway and above the monitoring location.

Attainment of load allocations is tied to structural and operational changes at each dam, and is intended as a long-term target. Short-term targets will be established under the implementation plan for dams below Chief Joseph, and will be based on operational management of spills, structural modifications, and compliance with Endangered Species Act requirements and TDG fish passage spill criteria.

Margin of Safety

A margin of safety is supplied implicitly by use of conservative critical conditions for ambient barometric pressure. The common occurrence of wind-induced degassing in the TMDL area also provides a margin of safety. The TDG criterion itself provides a margin of safety due to its stringency as compared to site-specific effects documented by extensive site-specific research on TDG and aquatic life in the Columbia River.

Seasonal Variation

Spills and associated high TDG levels, although most likely to occur in the spring and early summer, can potentially occur at any time. Therefore, TMDL load allocations apply year-round. Seasonal effects have been evaluated in the development of critical conditions, but seasonal variations appear to be small. The TMDL only applies for flows below the 7Q10 flood flows for waters below the Spokane River confluence. These flows have been calculated for each dam.

Monitoring Plan

Long-term targets with load allocation will be monitored at locations below the aerated zone with special studies in the tailrace of the dam, following structural modifications. Also, continuous monitoring will be used for long-term targets by determining the statistical relationship between continuous monitors and conditions at the designated monitoring location. Monitoring of implementation and operational controls in the short term will use continuous monitoring at fixed monitoring station sites.

Implementation Plan

The state and the Spokane Tribe have developed an implementation plan (See Appendix A). The Implementation Plan incorporates actions described and analyzed by NOAA Fisheries in the Biological Opinion and by the U.S. Army Corps of Engineers in its Dissolved Gas Abatement Study. Both short-term (Phase I) and long-term (Phase II) measures are described with specific TDG and spill reduction measures. Phase I is in effect through 2010. Phase II begins in 2011 and continues until 2020. The Implementation Plan has been developed in consultation with NOAA Fisheries, so that TMDL implementation will be coordinated with requirements of the Endangered Species Act.

Reasonable Assurance

Actions which will be utilized to implement this TMDL at federal dams through 2010 are consistent with the Reasonable and Prudent Alternative measures required under the Federal Columbia River Biological Opinion issued by NMFS. These measures are mandatory under the Biological Opinion and thus there is reasonable assurance that the measures needed to reduce TDG loading from these sources will be implemented.

Four of the five dams owned and operated by Public Utility Districts will be required to renew their FERC licenses between 2005 and 2028. As part of the re-licensing process each facility will be required to specify measures which will be implemented to attain water quality standards as part of the 401 certification process. These measures will be mandatory (as part of the permit), thus providing reasonable assurance of implementation.

Public Participation

There have been extensive public involvement activities, organized by the inter-agency TMDL Coordination Team. Activities include websites, focus sheets, coordination meetings, stakeholder meetings, conference presentations, and public workshops. Public hearings will be held in January 2004 (see *Summary of Public Involvement* Appendix A to this report).

Introduction

State and tribal water quality standards establish criteria at levels that ensure the protection of the water's beneficial uses. The Colville and Spokane Tribes and EPA are responsible for managing water quality for waters of the Colville and Spokane Reservations. The Washington State Department of Ecology is charged to assess, manage, and protect the beneficial uses of the waters of Washington State.

A number of waterbodies in the mainstem Columbia River fail to meet water quality standards and thus are included on Washington's 303(d) list. Under the Clean Water Act, Washington State is charged with returning state waters to compliance with state standards through development and implementation of Total Maximum Daily Load (TMDL). In developing a TMDL, the state should also consider attainment of downstream tribal or state water quality standards.

For Tribal Waters, the authority to issue TMDLs remains with EPA until individual tribes receive specific authorization to do so, thus EPA will be issuing this TMDL for Tribal waters. In addition, the state of Washington has requested that EPA issue the TMDL for state waters in Lake Roosevelt.

Washington State, the Colville Tribe, and the Spokane Tribe have each established criteria for total dissolved gas (TDG), which at high levels has deleterious effects on fish and other aquatic life. This document details a TMDL for TDG in the mainstem Columbia River from the international border with Canada to the mouth of the Snake River (Figure 1). This report will explain what TDG is, why high TDG is a problem, and a strategy for managing it so water quality standards will be met.

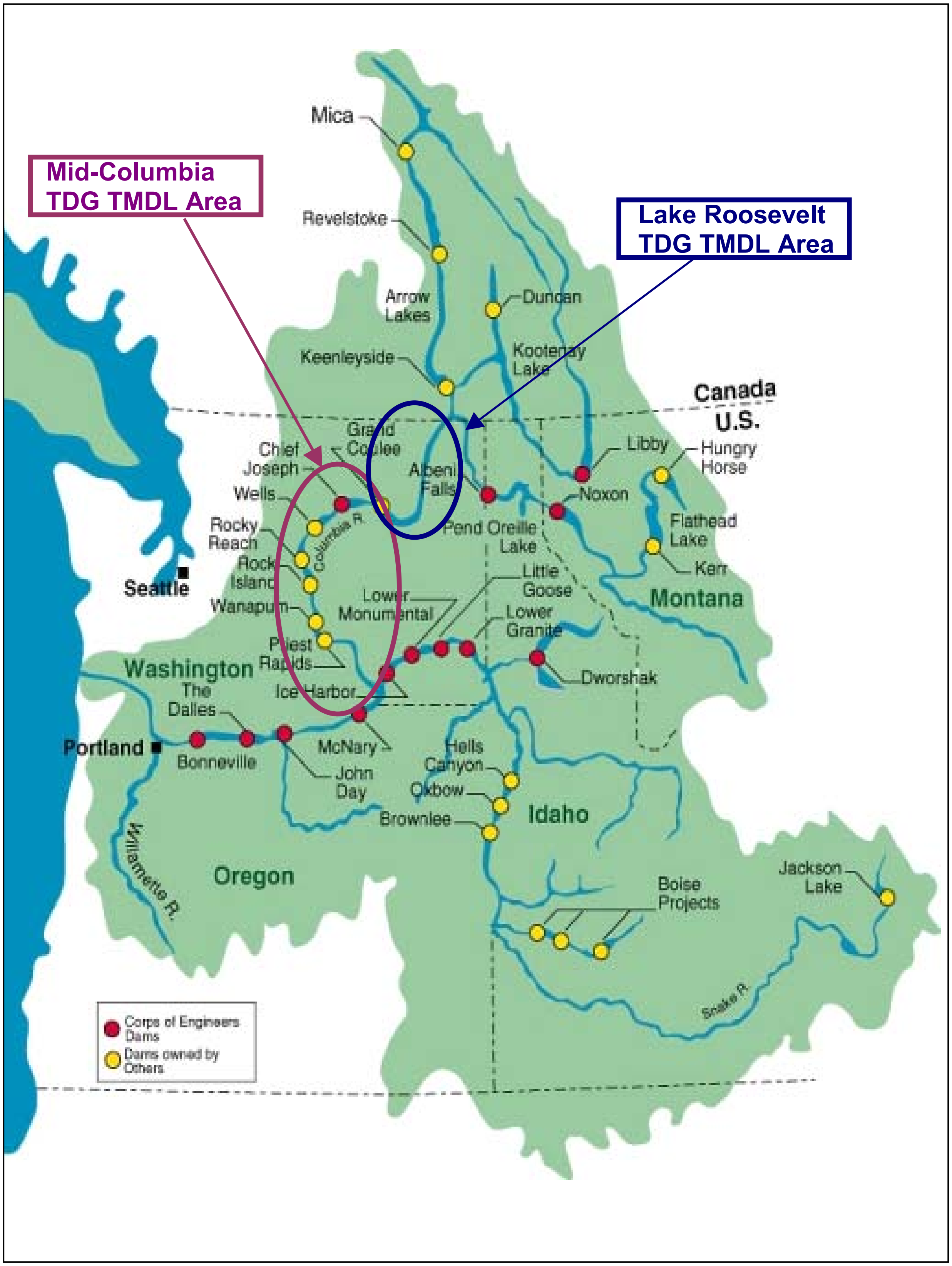

Figure 1: Map of the Mid-Columbia and Lake Roosevelt TMDL Area

Geographic Extent

This TMDL applies to the Columbia River mainstem from the international border with Canada to its confluence with the Snake River, including all waters up to the high water mark in Lake Roosevelt together with the Spokane River Arm.

The laws of Washington apply to the Columbia River from the U.S.-Canada border to the mouth of the Snake River, excepting waters located on the Colville and Spokane Reservations (Figure 2). All of the state waters have been included on Washington's 1996 303(d) list, 1998 303(d) list, or have been identified as impaired. The segments covered by this TMDL are listed in Table 1, along with the Water Resource Inventory Area (WRIA) and Waterbody Identification (WBID) numbers.

Table 1: Washington's Mid-Columbia River and Lake Roosevelt TDG Listed and Impaired Segments

Segment description	WRIA	WBID	1996 303(d) listings	1998 303(d) listings
Snake River Confluence to Priest Rapids Dam		*WA-CR-1030*		
Alkali-Squilchuck	40	NN57SG	2	2
Chief Joseph Dam to Priest Rapids Dam		*WA-CR-1040*		
Alkali-Squilchuck	40	NN57SG	2	2
Lower Crab	41	NN57SG	1	1
Wenatchee	45	NN57SG	2	2
Chelan	47	NN57SG	2	2
Foster	50	NN57SG	1	1
Grand Coulee Dam to Chief Joseph Dam		*WA-CR-1050*		
Foster	50	NN57SG	1	1
Lower Lake Roosevelt Watershed	53	NN57SG	3	3
Canadian Border to Grand Coulee Dam		*WA-CR-1060*		
Upper Lake Roosevelt Watershed	61	NN57SG	3	3
Totals			17	17

The Colville Reservation borders Lake Roosevelt on the west and north for 100 miles upstream of Grand Coulee dam. The reservation forms the northern shore of the Columbia River downstream of Grand Coulee Dam to the confluence of the Okanogan River between Chief Joseph and Wells dams. Therefore, Colville Tribal waters include those portions of Lake Roosevelt and the Columbia River within reservation boundaries, and the Colville Tribes' water quality standards apply in these waters.

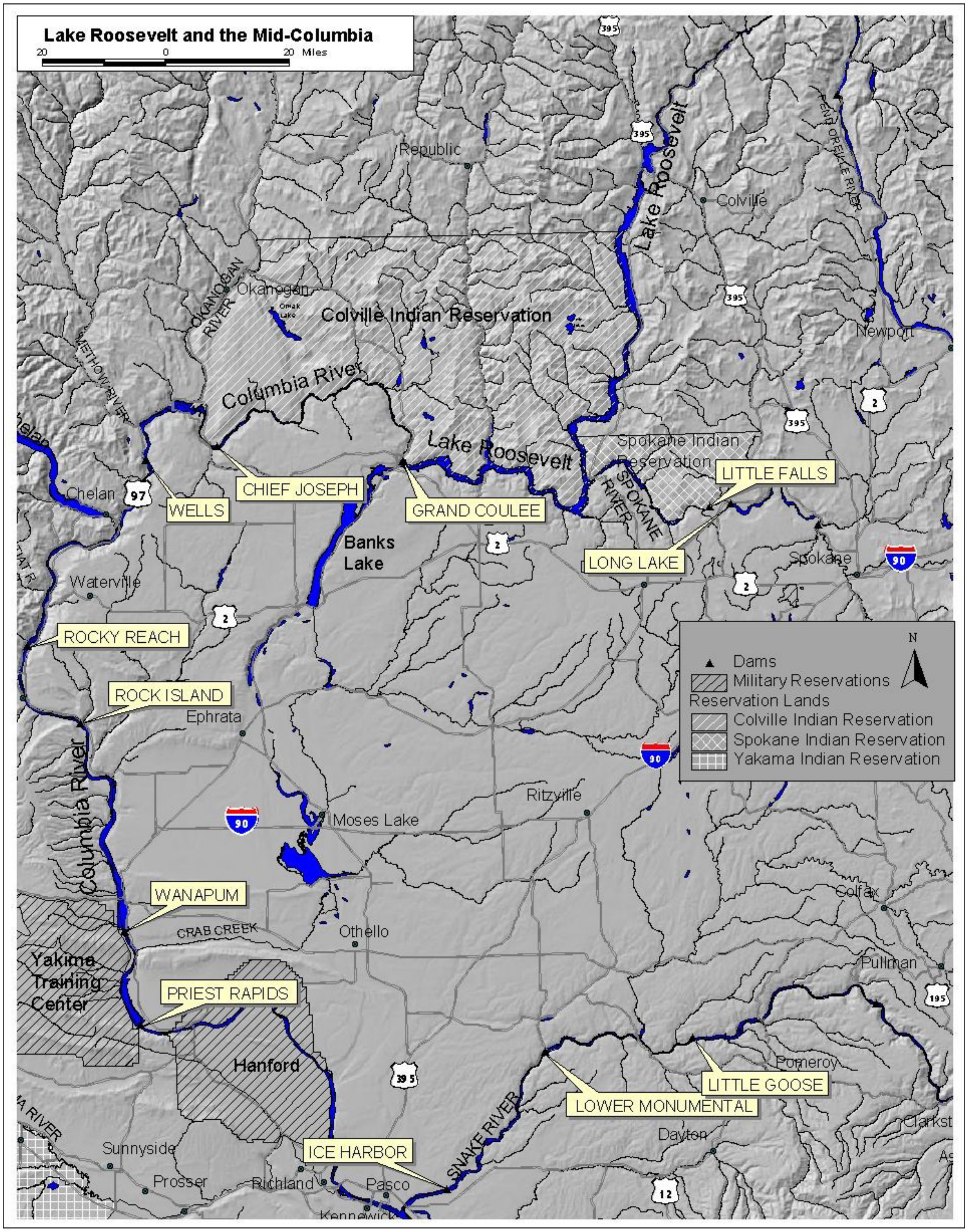

Figure 2: Lake Roosevelt and the Mid-Columbia

The Spokane Indian Reservation borders Lake Roosevelt on the eastern shore, in the area upstream of the Spokane River confluence. Spokane tribal waters include a portion of Lake Roosevelt including all of the Spokane River Arm. The Spokane Tribe has approved water quality standards for those waters within its southern and western reservation boundaries that lie within the TMDL area.

TMDLs for TDG have been completed for the Lower Columbia River by the states of Oregon and Washington, and for the Lower Snake River (Clearwater River to confluence with the Columbia River) by Washington. Those two TMDLs provide guidance as to the TDG levels that will need to be attained at the downstream end of this reach in order to achieve downstream water quality standards.

Clean Water Act Requirements

Water quality monitoring has shown that during certain times of the year TDG levels in the Columbia River between the Canadian border and the confluence with the Snake River exceed these standards. Table 1 summarizes the portions of the river listed as impaired for TDG pursuant to section 303(d) of the Clean Water Act. On its 1998 303(d) list, Washington listed 17 different segments of Lake Roosevelt and the Columbia River above the Snake River confluence for impairment by TDG.

As a result of these listings and under the authority of the Clean Water Act (33 U.S.C. 1251 et seq.) as amended by the Water Quality Act of 1987 (P.L. 100-4) the U.S. Environmental Protection Agency (EPA) and Washington Department of Ecology (Ecology) are establishing these Total Maximum Daily Loads (TMDLs) for total dissolved gas (TDG) in the mainstem of the Columbia River, from the Canadian border to the confluence of the Snake River. EPA is establishing the TMDL for all waters above Grand Coulee Dam, and for waters below Grand Coulee Dam within the Colville Indian Reservation. EPA and Ecology have been working in coordination with the Spokane Tribe throughout the process of developing this TMDL. The Colville Tribe has had limited involvement with the TMDL.

The Washington Department of Ecology requested by letter that EPA establish the TMDL for TDG in Lake Roosevelt. Ecology also cited the inter-jurisdictional nature of the waterways as the reason for its request. The request was made pursuant to Section 13 of the TMDL Memorandum of Agreement between Ecology and EPA dated October 29, 1997.

EPA has authority under section 303(d)(2) of the Clean Water Act (CWA) to approve or disapprove TMDLs submitted by the states and tribes and to establish its own TMDLs in the event that it disapproves a state or tribal submission. EPA also has the authority under section 303(d)(2) to establish TMDLs in response to an explicit state request. EPA's exercise of authority to establish TMDLs in response to a state's request is consistent with the larger purpose of section 303(d)(2) – to ensure the timely establishment of TMDLs – and it honors the primary responsibility imputed by Congress to the states. In addition, when the TMDL focuses on inter-jurisdictional waters, EPA's involvement can facilitate the resolution of complex cross-jurisdictional problems that might be difficult for an individual state or tribe, acting alone, to resolve. For similar reasons, EPA has authority to establish TMDLs on behalf of tribes that have not been authorized to establish TMDLs under section 518(e) of the CWA.

Therefore, the goal of this project is to provide a single analysis and set of TMDL allocations which will lead to attainment of the TDG criteria established for waters of Washington State and the Colville and Spokane Tribes. An implementation plan has been developed by Ecology and the Spokane Tribe which identifies actions to be taken to achieve the allocated loads. This plan, the Summary Implementation Strategy (SIS), has been developed by the State and Tribe under State, Tribal, and Federal authorities. A copy of the SIS is attached to this document in Appendix A.

A TMDL determines the quantity (load) of a pollutant that can enter a waterbody and still meet water quality standards. This load is then allocated among the various sources. The SIS identifies actions that appropriate agencies and stakeholders will undertake to achieve the allocated loads.

Coordination with Endangered Species Act

A TMDL is a planning tool, not a rule of law or other stand-alone enforceable document. It does not take precedence over the federal Endangered Species Act, Indian Treaties, or federal hydropower system enabling legislation. It takes no action that would trigger a review under the National Environmental Policy Act or Washington State Environmental Policy Act. TMDLs may be used to condition exemptions, modifications, variances, permits, licenses, and certifications.

There is much overlap between protection of the fisheries designated use in this TMDL established pursuant to the federal Clean Water Act and the protection of salmonids listed as threatened or endangered under the Endangered Species Act, administered by the National Marine Fisheries Service (NMFS). It is therefore important that there is a clear understanding of the requirements of this TMDL relative to measures required by Biological Opinions issued in relation to the threatened and endangered species of the Columbia River.

The 2000 Federal Columbia River Power System (hydropower system) Biological Opinion requires that the action agencies (U.S. Army Corps of Engineers, Bonneville Power Administration, and the U.S. Bureau of Reclamation) meet specific hydropower system biological performance standards for both adult and juvenile salmon. The purpose of these standards is to help reverse the downward trend in listed salmon populations and therefore ensure viable salmon resources in the Columbia River Basin. The hydropower system goals for juvenile salmon are one part of a three-tiered approach to assess implementation of the Reasonable and Prudent Alternative Section items presented in the Biological Opinion. These hydropower system standards are combined with standards for harvest, habitat, and hatcheries and other life stage indicators to arrive at a population level standard.

The hydrosystem survival performance standards can be met by a combination of controlled spills, fish passage facilities to divert juvenile salmon from passing through the turbines, or juvenile transportation by truck or barge. Due to the current configuration of the hydroelectric projects along the Columbia River, NMFS sees spill as the safest, most effective tool available for improving survival of juvenile outmigrants. However, these performance standards are not being met at the current implementation level of the spill program. Therefore, in the short-term, structural gas abatement solutions may result in higher spill discharges rather than lower TDG levels. But as new, more effective fish passage facilities are completed and evaluated, their contribution to the attainment of hydropower system performance standards will hopefully allow spill levels for fish passage and associated TDG levels to be reduced, but only as long as the performance standards are met.

Spills for fish passage under the Biological Opinion cause TDG supersaturation above the 110% criterion. The state and tribal water quality standards are meant to be sufficiently protective so as to prevent damage to beneficial use of the tribal and state waters. The effects of elevated dissolved gas on migrating juvenile and adult salmon due to voluntary spill have been monitored each year of spill program implementation. Based on five years of data from the biological monitoring program, the average incidence of gas bubble disease signs has been low, although the state-allowed maximum TDG due to spill was 120% in the tailrace and 115% in forebays. From 1995 to 1996, only 1.6% of all the juveniles sampled, nearly 200,000 fish, showed signs of disease (Schneider, 2001). These results suggest that, in weighing the benefit gained in increased salmon survival by spills for fish passage against the benefit from strict adherence to the 110% TDG criterion in the standards, it would be reasonable to find flexibility in application of the standards.

Chief Joseph and Grand Coulee dams are barriers to fish migration. There are no anadromous species present in the river above Chief Joseph Dam. Release of water is required from both Chief Joseph and Grand Coulee dams to facilitate the requirements of the NMFS Biological Opinion for fish passage in the downstream portions of the river. These dams are in waters shared between the State and the Colville Tribe. It is anticipated that Grand Coulee Dam will be able to meet the need for additional flow without spilling, under the terms of the proposed power trading arrangement between the two dams. Fish augmentation flow through Grand Coulee Dam's turbines sometimes necessitates involuntary spill at Chief Joseph Dam.

Funding was approved this year for the flow deflector project at Chief Joseph, with installation targeted for 2005, subject to continued funding. This structural retrofit in conjunction with the power trading agreement is expected to reduce TDG levels in Chief Joseph tail race to levels equivalent to those in the forebay or no net increase of TDG from the dam operation.

In summary, the provisions of both Acts must be met. Notwithstanding that, it is not the purpose of the Clean Water Act to usurp functions properly undertaken pursuant to the Endangered Species Act. On the contrary, EPA has consulted with NMFS and FWS under section 7 of the Endangered Species Act to ensure the TMDL does not cause jeopardy to any listed species. Over time the State and Tribes and EPA will continue to coordinate with NMFS and FWS as implementation measures needed to attain load allocations are pursued.

This TMDL is written to reflect the ultimate attainment of the TDG water quality standard. Fish passage requirements can be facilitated under an implementation plan, but the clear expectation of the Clean Water Act is that water quality standards will be attained in a limited amount of time. Efforts to do so are outlined in the attached Summary Implementation Strategy (Appendix A).

Total Dissolved Gas Water Quality Standards

The goal of this TMDL is to achieve all of the TDG criteria established within state and tribal water quality standards. The criteria for all three entities are similar, although there are differences between them which will need to be considered during the implementation of this TMDL. The water quality standard relative to TDG for each jurisdiction is outlined below followed by a discussion of the target to be used in this TMDL to assure attainment of all five sets of criteria.

In the water quality standards, TDG is defined as the percent of saturation relative to atmospheric pressure. The "ten-year, seven-day average flood" or "seven-day, ten-year frequency flood" are usually termed the "7Q10" flood flows.

State of Washington Standards

Washington's Water Quality Standards, Chapter 173-201A Washington Administrative Code (WAC), describes the water quality standards.

WAC 173-201A-200(1)(f): Aquatic Life total dissolved gas (TDG) Criteria.

TDG is measured in percent saturation. Table 200(1)(f) (see Table 2) lists the maximum TDG criteria for each of the aquatic life use categories.

(i) The water quality criteria herein established for TDG shall not apply when the stream flow exceeds the seven-day, ten-year frequency flood.

(ii) The TDG criteria may be adjusted to aid fish passage over hydroelectric dams when consistent with a department approved gas abatement plan. This plan must be accompanied by fisheries management and physical and biological monitoring plans. The elevated TDG levels are intended to allow increased fish passage without causing more harm to fish populations than caused by turbine fish passage. The following special fish passage exemptions for the Snake and Columbia rivers apply when spilling water at dams is necessary to aid fish passage:

- TDG must not exceed an average of 115% as measured in the forebays of the next downstream dams.
- TDG must not exceed an average of 120% as measured in the tailraces of each dam;
- TDG is measured as an average of the 12 highest consecutive hourly readings in any one day, relative to atmospheric pressure; and
- A maximum TDG one-hour average of 125% must not be exceeded during spillage for fish passage.

Table 2: Aquatic Life TDG Criteria from the Washington State Code

Table 200(1)(f): Aquatic Life Total Dissolved Gas Criteria in Fresh Water	
Category	Percent Saturation
Char	TDG shall not exceed 110% of saturation at any point of sample collection.
Salmon, Steelhead, and Trout Spawning, and Rearing	Same as above
Salmon, Steelhead, and Trout Rearing – Only	Same as above
Non-anadromous Interior Redband Trout	Same as above
Indigenous Warm Water Species	Same as above

Colville Tribe Standards

The Colville Tribe's Water Quality Standards, Chapter 4-8 of the Colville Law and Order Code, set the following criteria for Tribal waters covered under this TMDL:

Total dissolved gas shall not exceed 110 percent of saturation at any point of sample collection. (Colville Water Quality Standards Code 4-8-6(a)3E & 4-8-6(b)3E)

The Water Quality Standards herein established for the total dissolved gas shall not apply when the stream flow exceeds the 7-day, 10- year frequency flood. (Colville Water Quality Standards 4-8-5(e))

Spokane Tribe Standards

The Spokane Tribe's Surface Water Quality Standards, Chapter 30, Resolution 2001-144 of the Spokane Tribal Council, set the following criteria for Tribal waters covered under this TMDL:

Total dissolved gas shall not exceed 110 percent of saturation at any point of sample collection. (Spokane Tribe's Surface Water Standards 9 (1) (c) (iii) & (2) (c) (iii)

Summary

The three water quality standards all set 110% saturation as the target for TDG in waters under their jurisdictions, and this will be the target of this TMDL. The Washington State and Colville Tribe allow exceedance of the 110% standard at flows above the 7Q10 flow. The Spokane Tribe standard does not have this exception to the standard. In the portion of Lake Roosevelt in or above Spokane Tribal waters and in the Spokane Arm the 7Q10 exemption will not apply.

The State of Washington allows exceedance of the 110% criteria to facilitate fish passage spills. The Colville and Spokane Tribal standards do not contain any allowance for higher TDG values during spill for fish passage. In waters upstream of the Okanogan River, 110% TDG saturation will be the target used in the TMDL, with no exemption for fish passage spills. Downstream of the Okanogan River, allocations will be provided based on Washington's fish passage criteria.

Background

Sources of Total Dissolved Gas

Total dissolved gas (TDG) levels can be increased above the water quality criteria by spilling water over spillways of dams on the Columbia River. There are a variety of other ways that TDG may be elevated: passage of water through turbines, low level ports, fishways, or locks; and natural processes such a low barometric pressure, high water temperatures, or high levels of biological productivity. However, the vast majority of the elevated TDG levels found in the Columbia River are caused by spills from dams. Man-made sources other than spill are minor, and can be considered negligible. Natural processes may have a significant effect on TDG, and are addressed in setting load allocations.

Spills at dams occur for several reasons:

1. To enhance downstream fish passage (to meet "Performance Standards" for fish survival under the Endangered Species Act).
2. To bypass water that exceeds the available hydraulic capacity of the powerhouse due to:
   - High river flows.
   - Lack of power market.
   - Maintenance, break-down, or other reasons.

The first type of spill is sometimes called "voluntary spill", while the second types are termed "involuntary spills". Figure 3 illustrates the typical configuration of a dam on the Columbia River.

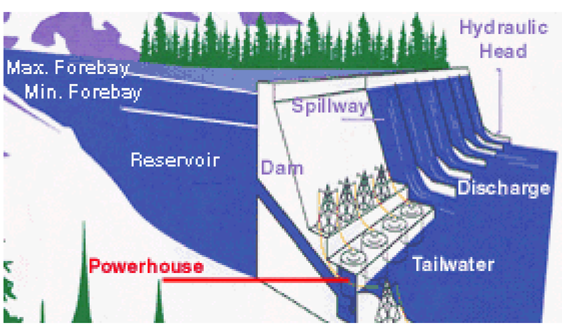

Figure 3: Typical Dam Configuration

Spill for Fish Passage

Spill for purposes of fish passage involves water deliberately released over dam spillways, rather than being discharged through turbines or fish bypass facilities. The intent is to reduce turbine and bypass mortalities. For example, Schoeneman et al. (1961) found that mortality in Chinook juveniles spilled over McNary Dam (Columbia River) and Big Cliff Dam (Santiam River) was less than two percent. Subsequent studies confirmed this estimate, and research is ongoing. The requirement for spring and summer spills to pass juvenile salmon was included in the 1995 and 2000 Biological Opinions for the Columbia River dam operations. In order to account for these needs, the State of Washington has established the special TDG limits to allow limited fish passage spill.

Washington's approach to allow the dams to operate in accordance with the Biological Opinion was to adopt a rule revision specifying the TDG criteria for fish passage spill. These limits usually require TDG levels not exceed 120% saturation as a 12-hour average and 125% saturation as a one-hour maximum relative to atmospheric pressure in the tailrace of the spilling dam, and 115% TDG saturation as measured in the forebay of the next dam downstream. Periods in which the fish passage criteria are in effect usually extend from the middle of April through the end of August each year. No similar exemptions currently exist with either the Spokane or Colville Tribes.

Involuntary Spill

Like spills for fish passage, involuntary spill involves water being discharged over dam spillways. However, the causes and intended consequences are different. As its name suggests, there is no choice involved in "involuntary" spill. At times of very high river flows, the quantity of water exceeds the capacity of a dam to either temporarily store the water upstream of the dam or pass the water through its turbines. In these circumstances, water is released over the spillway, because there is nowhere else for it to go. The Columbia River hydropower system in Washington is somewhat unique in that regard. With the exception of Grand Coulee Dam, it contains very little storage potential relative to the quantity of spring runoff. At times of rapid runoff, the dams cannot constrain the quantity of water, and it is spilled with attendant high TDG levels. Often dissolved gas levels from involuntary spill exceed those experienced during periods of spill for fish. However, high river flows under these circumstances are often in excess of the 7Q10 flood flow, in which case the TDG standards of the state and Colville Tribe do not apply. The Spokane Tribe has no exemption for 7Q10 flood flows in their proposed water quality standards.

Involuntary spill as a result of lack of power market is a variant of the above. In this scenario, the power marketing authority cannot sell any more power, and even though turbines are available, water is released over the spillway because there is nowhere for electricity generated to go. Running water through the turbines with no load increases wear and tear with attendant higher maintenance costs, and also may reduce fish survival. Lack of power load demand can occur at times of both high and low flows (e.g., in the spring or fall when power demands are low both in California and the Pacific Northwest). Also releases from upstream storage dams during high load times (morning and evening) can result in high flows at downstream dams during low load times (middle of the night), causing an involuntary spill.

Involuntary spill can also occur at low flows when powerhouses are taken off-line for maintenance, breakdown, or other needs. Maintenance is usually scheduled to prevent a spill, by doing maintenance on one or two generating units at a time during low power demand periods. Nonetheless, releases from upstream dams can complicate management of spills during powerhouse maintenance. Also, unscheduled maintenance and repairs sometimes occur, which may require a powerhouse shut-down and involuntary spill.

In general, involuntary spill conditions at the “run of the river” dams may result from reservoir control and power marketing decisions made by the federal project operators having storage capacity upstream. Improved accuracy in water forecasting could help avoid understating or overstating available water supply, which could cause the federal project operators to spill water because they left too little or too much room in the reservoirs. Additionally, a water management plan could also identify uncoordinated releases and manage intra-day fluctuations in river flows. These events often result in isolated involuntary spill events, because reservoir elevation must be maintained within limits at run of the river projects.

Water Quality and Resource Impairments

TDG Generation from Spills

Spills for fish passage typically occur during the spring and summer months. During periods of fish spills, deviations of ambient conditions from the state of Washington's TDG criteria for fish passage (described above) are frequent but usually small. This is because spill quantities are managed to meet those criteria.

The excursions beyond criteria usually have been no more than one or 2% above the criteria, and occur as a result of the imprecision in reproducing exact TDG levels at specific spillway gate set points due to all the sources of TDG variability described. Generally, the fishery management agencies have sought spill quantities in order to remain right at the TDG criteria at the fixed monitoring station sites. Any small change in conditions that influence TDG, such as change in barometric pressure, water temperature, incoming gas, total river flow or tailwater elevation will cause an exceedance when operated this way.

As described above, no similar relaxation of the standard currently exists for fish passage spills in either the Spokane or the Colville water quality standards. Most of the time during the spring and summer, TDG levels do not meet the 110% criterion of both tribes.

Involuntary spills can occur at any time. Involuntary spills caused by river flows above powerhouse capacity are most likely to occur from late fall to early summer, depending on rainfall or snowmelt in the tributary watersheds. However, high flows could also occur due to releases from upstream dams with significant storage, such as Grand Coulee or the Canadian dams. Involuntary spill due to low power demand is most likely in the spring, although this is also dependent on regional power management by the Bonneville Power Administration. Loss of powerhouse capacity to maintenance or repair is usually scheduled so that no more than one or two turbines are out at any given time, but an emergency powerhouse shutdown and spill could occur at any time as the result of a fire or other disaster.

At times of involuntary spill, exceedances above the standard can rise dramatically, peaking above 130% of saturation, and even 140 percent. Absolute TDG pressures at these levels, which usually only occur in shallow waters, can be lethal to fish. Usually fish are protected from fatal pressures in deeper waters by compensation from hydrostatic pressures, which reduces absolute TDG levels.

For all spills, the highest TDG levels, and therefore the area most likely to exceed standards, are directly below the spillway. In this area, the plunging and air entrainment of the spill (aerated zone) generates high levels of TDG, but then quickly degasses while the water remains turbulent and full of bubbles. However, as this water moves from the stilling basin into the tailrace, degassing slows and the TDG levels stabilize.

In the pools, gas exchange rates increase as wind speeds rise, which produces degassing. If conditions are still and TDG concentrations are constant, the percent saturation of TDG can increase if the water temperature increases or barometric pressure drops (Figure 4). Also, primary productivity (periods of algal growth) can increase dissolved oxygen levels, which results in a higher TDG percent saturation. However, because oxygen is metabolized by the aquatic life, the physical effects of supersaturated oxygen are minor compared to nitrogen and can be considered *de minimus.*

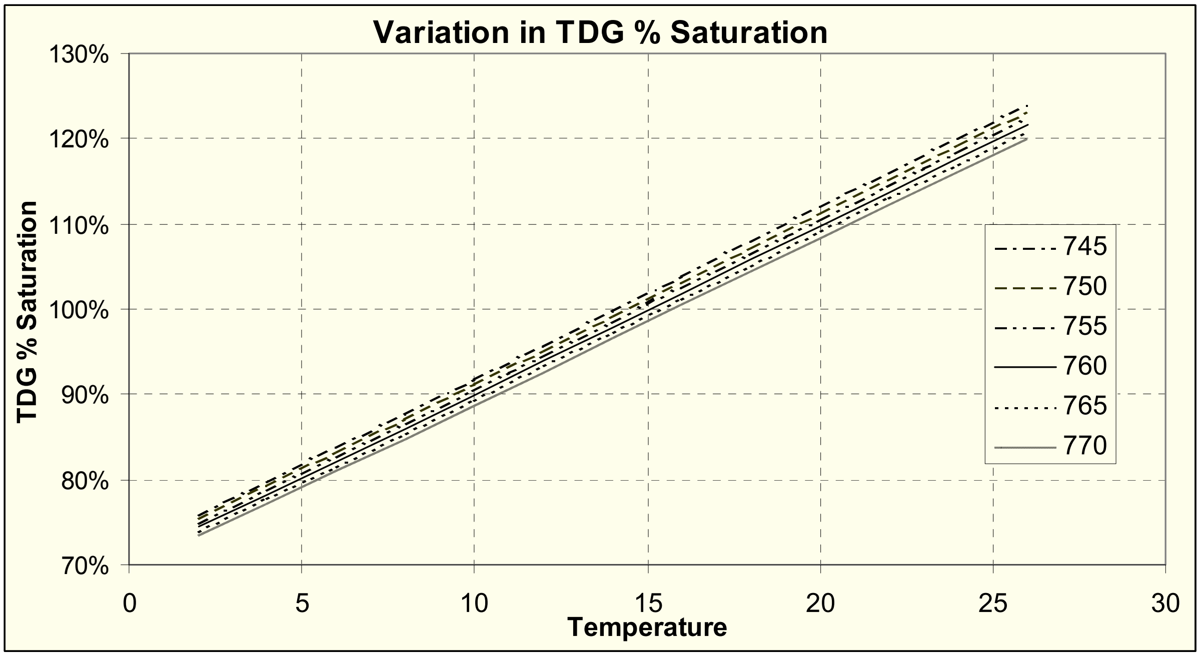

Figure 4: Variation in TDG Percent Saturation with Temperature and Barometric Pressure at Constant Concentration

Due to the hydraulic properties of the spill, a proportion of the powerhouse flow entrains with the spill and is aerated as if it were part of the spill. The rest of the powerhouse flow mixes with the spillway flows at varying rates, sometimes quite slowly, as the river moves downstream from the dam. Powerhouse TDG levels are typically identical with forebay TDG levels – very little gas exchange occurs as water passes through the powerhouse. Therefore, if the forebay TDG levels are lower than levels below the spillway, the powerhouse flows that mix slowly and farther downstream will reduce the TDG levels in the spillway waters by dilution.

TDG Impacts on Aquatic Life

Fish and other aquatic life inhabiting water supersaturated with TDG may tend to display signs of difficulty, especially if higher dissolved gas pressure gradients occur. Gas bubbles form only when the TDG pressure relative to atmospheric pressure is greater than the sum of the compensating pressures. Compensating pressures include water (hydrostatic) and barometric pressure. For organisms, tissue or blood pressure may add to the compensating pressures. Gas bubble development in aquatic organisms is then a result of excessive uncompensated gas pressure. The primary actions which will enhance the likelihood of bubbles forming in the fish are (1) continued exposure to the highly saturated water, (2) rising higher in the water column bringing about a higher pressure gradient (decreased hydrostatic pressure), (3) decreases in barometric pressure, and (4) increasing water temperature.

The damage caused by release of gas bubbles in the affected organism is termed gas bubble trauma or gas bubble disease. There is a wide body of research on this condition. Effects of gas bubble trauma include emphysema, circulatory emboli, tissue necrosis, and hemorrhages in brain, muscle, gonads, and eyes (Weitkamp and Katz, 1980). Nebeker et al. (1976) found that death in adults was due to massive blockages of blood flow from gas emboli in the heart, gills, and other capillary beds. Investigators in the 1970s reported many and varied lesions in fish exposed in the 115%-to-120% TDG range in shallow water. At higher gas exposures (e.g., 120% to 130% TDG) death frequently ensued before gas bubble trauma signs appeared (Bouck et al., 1976). External signs of gas bubble trauma (e.g., blisters forming in the mouth and fins of fish exposed to chronic high gas) often disappeared rapidly after death. The signs were largely gone within 24 hours (Countant and Genoway, 1968).

A water quality criterion for TDG was set at 110 percent, the threshold for chronic effects found in the literature. The severity of gas bubble trauma increases as the TDG level increases above compensating pressures, until at higher levels lethality can occur swiftly. However, there are a number of factors that affect a particular organism's response to high TDG levels. Different species respond to changing TDG differently, and the response also varies by life stage. Juvenile salmonids appear to be relatively resilient compared to adults or to non-salmonids.

Scholz et al. (2000) conducted surveys of fish in Lake Roosevelt to assess the extent of GBT in fish after the extremely high TDG levels during 1997 runoff. This study looked at 9,319 fish from 29 species, and found over 65% of fish exhibiting symptoms of GBT. Ten species had sample sizes of over 100. Of these 10 species, the two species with the lowest percent of GBT symptoms were both from *Salmonidae* – Kokanee and Rainbow trout – and had 14.2% and 22.0% with symptoms, respectively. The two species with the highest percent of symptoms from this subsample were Largescale Sucker and Burbot, which showed 85.5% and 86.9% with symptoms, respectively. Sampling of Largescale Sucker in Lake Roosevelt between 1996 and 1999 indicated a loss of 90-95% of the population of that species, with a gap in the age distribution corresponding to the high TDG years of 1996 and 1997.

Other research has been conducted on the effects of TDG on anadromous fish in the Columbia River. It is beyond the scope of this TMDL to conduct a comprehensive review of that literature. The Clean Water Act requires compliance with existing standards, although existing research can be used to aid in interpretation of those standards. A review of the standards to look at adoption of different criteria, duration, frequency, and spatial application, if appropriate, would occur through a completely separate process. If new standards were adopted, then the TMDL could be reviewed and possibly revised.

It is possible that TDG became elevated under historical natural conditions in the Columbia River, such as below Kettle Falls. However, elevated TDG probably dissipated quickly as it passed over shallows and rapids. Conditions different from natural conditions exist at the Columbia dams that create high TDG levels. These conditions include the height of the dams, the shape of the spillways, and the presence of the long deep pools below the dams. Allowing a monitoring point below the aerated portion of the tailrace can be considered to reflect gas generation patterns in a natural system.

TDG levels can become elevated due to oxygen produced as part of primary productivity. Generally this form of TDG is considered to be much less harmful to aquatic life, since oxygen can be metabolized by aquatic organisms.

Monitoring of TDG

TDG is monitored *in* situ using a direct-sensing membrane diffusion method described in Standard Method 2810B (APHA, AWWA, and WEF, 1998). There are several manufacturers of available equipment, and field methodologies vary between the organizations that conduct monitoring. Most of the major monitoring programs (e.g. Corps, USGS) have well-documented methodologies and quality control procedures.

Routine monitoring of instream TDG levels occur at fixed monitoring station (FMS) sites above and below each dam and the international border with Canada. The tailwater FMS sites in some cases may be a mile or two downstream of the dam. The FMS sites have been the primary point of monitoring and assessment of TDG levels, especially for compliance with TDG criteria during fish passage spills. The locations have been chosen for a variety of reasons, a primary one being the logistics and feasibility of long-term monitoring. However, studies suggest that some of these sites are not collecting data that are representative of river conditions. The FMS sites will continue to be the primary location for determining attainment of TDG saturation limits used for fish passage management. For the purposes of TMDL compliance, TMDL requirements do not need to drive FMS siting issues.

The interagency Water Quality Team manages issues regarding the fish passage program and FMS. The Water Quality Team is jointly chaired by NMFS and EPA. It is charged with providing technical advice and guidance on temperature and total dissolved gas water quality in the context of the NMFS 2000 Biological Opinion relating to the Columbia River Hydropower System. A subgroup of that team has been addressing concerns with the FMS sites, and the appropriateness of the current FMS locations has been the subject of vigorous debate between the resource agencies and U.S. Army Corps of Engineers within the subgroup. The subgroup has concluded that the "representativeness" of FMS data is a very difficult characteristic to define. The TDG measurements at a given location in the river are influenced significantly by environmental factors such as water temperature, biological productivity, barometric pressure, and wind, as well as the spill. The Water Quality Team will continue to study and discuss these issues in order to achieve a mutually satisfactory monitoring end product.

To gain additional knowledge of TDG conditions in the river, the Corps has conducted a number of detailed special studies of TDG levels below the dams (e.g., Schneider and Wilhelms, 1996; Wilhelms and Schneider, 1997a; Wilhelms and Schneider, 1997b; Schneider and Wilhelms, 1999). These studies have shown that TDG levels measured at the FMS sites are usually lower than levels longitudinally upstream towards the spillway, may be lower than levels laterally across the river if powerhouse flows are not fully mixed, and in some conditions may be lower than levels longitudinally downstream.

Analysis of Current Conditions

TDG Data Sources

TDG data were available on many of the projects from several sources: the fixed monitoring station (FMS) system; other long term monitoring stations; near field (tailrace) and spillway performance tests; limnology sampling; and in-pool transport and dispersion tests. Operational data were obtained from many projects detailing the individual spillway and turbine discharge on an interval ranging from five minutes to one hour.

Sources of data included: U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, Environment Canada, Spokane Tribe, BC Ministry of Water, Land and Air Protection, Columbia River Integrated Environmental Monitoring Program, U.S. Geological Survey, BC Hydro, Teck Cominco, Aquila, City of Seattle, Avista, Chelan County PUD, Grant County PUD, Douglas County PUD, Golder Engineers, and Aspen Applied Sciences.

Data Quality

Data quality assurance/quality control procedures varied greatly for the source information used in this TMDL. This is particularly true of the data collected above Grand Coulee Dam that was used in the discussion of sources to Lake Roosevelt. The data quality assurance and control procedures for each source are discussed in detail in Appendix E.

Lake Roosevelt TMDL Data

Data from a large number of sources was utilized to evaluate the contribution of sources in Canada as well as conditions at the boundaries and within the lake. The quality and type of data was variable. A synopsis of the data types is provided below.

U.S. Bureau of Reclamation Data

There are two fixed monitoring stations at either end of the lake maintained by the U.S. Bureau of Reclamation. The station at the Canadian border has collected TDG data since 1995. The other station, in the forebay of Grand Coulee Dam, has collected TDG data since 1997. The data used in this report has not been through quality control. Data collected at these stations includes TDG, temperature, and barometric pressure.

The forebay monitor is set 15 feet below minimum pool and 97 feet below maximum pool. The downstream monitor is understood to represent conditions where all flows – spillway, outlet works, and powerhouses – are fully mixed.

Concerns have been raised about whether the international border FMS data represents an average cross-sectional TDG value. Water quality data from the boundary station can be compared to data from the Kootenai and Pend Oreille rivers, and from the Columbia upstream of those two tributaries. During certain times of the year, the boundary station shows a bias towards conditions in the Pend Oreille, suggesting that river flows are not fully mixed at the boundary. This may only occur during certain flow conditions, and may only be observable when conditions in the tributaries are significantly different from the mainstem.

A one-day study was done at this site in the late 1990's. A cross-section was made with a hydrolab collecting grab samples. The study concluded that TDG was consistent. There is concern that the study was not extensive enough and may only be representative during a portion of the spill season. More study is needed to determine under which conditions data from the boundary station is not representative because of incomplete mixing across the channel.

U.S. Geological Survey Data

USGS maintains a fixed monitoring station for flow on the Columbia River just below the international border. The data used in this report has not been through quality control.

Spokane Tribe Limnology Data

Total dissolved gas pressure, barometric pressure, temperature, and dissolved oxygen along with a number of other water quality parameters were recorded at 11 sites in the reservoir in 2001 and 2002. Sampling was bi-weekly during the spring, summer and fall, and monthly during the winter months. The tribe released the 2001 data to Ecology and EPA with the understanding that it had not been through a quality control process.

Avista Data

Avista collected hourly water quality data in the tailrace of Little Falls Dam on the Spokane River from spring 1999 through winter 2002 as part of their upcoming FERC relicensing. The parameters tested include TDG, barometric pressure, temperature, and dissolved oxygen. Records of spill and generation flow for this dam were also kept by Avista and used in the TMDL. This data has undergone a review of data quality. Additional data were collected in 2003 on five of Avista's Spokane River hydroelectric projects (but not at Little Falls Dam), but were not used in this TMDL.

Columbia River Integrated Environmental Monitoring Program (CRIEMP) Data

CRIEMP includes Canadian utilities, the BC Ministry of Water, Land and Air Protection and Environment Canada. This group has collaborated in efforts to gather data in the transboundary Columbia system between 1995 and 2000. Most of the data were collected and reported on by Golder Engineers, although equipment from many sources was used. Collection intervals varied from five minutes to one hour depending on the sampling site and the study. Data were collected at nine long-term and eight short-term monitoring stations. This was augmented by grab sample data from a number of sites. Data collected included TDG, temperature, barometric pressure and dissolved oxygen.

In addition to the water quality data, spill and generation flow data was recorded by the dam operators in CRIEMP: BC Hydro, Teck Cominco, Aquila (previously Utilicorps), and Columbia Power Corporation/Columbia Basin Trust. Spill and generation data was utilized from Brilliant, Corra Linn and Kootenai Canal projects on the Kootenai River, and Waneta and Seven Mile dams on the Pend Oreille River. Spill and low level opening flow collected at Hugh Keenleyside Dam on the Columbia River was also used. Stream flow data was collected at Birchbank station on the Columbia River below the Kootenai River Confluence by Environment Canada.

Seattle City Light Data

Seattle City Light contracted with the U.S. Geological Survey to collect TDG and barometric pressure data in the forebay and the tailrace of Boundary Dam on the Pend Oreille from 1999 to 2003. Seattle City Light released the data to us with the understanding that it had not been through a quality control process.

Use of the Data

The data from the USBR FMS stations was used to understand the magnitude and season of impairment at both ends of Lake Roosevelt. Data from the international border FMS was used in conjunction with the CRIEMP, USGS, USBR and Seattle City Light data to understand and discuss the impacts of sources in Canada and the U.S. portion of the Pend Oreille River. Aspen Applied Sciences used these data sets to calibrate their model of TDG in the transboundary Columbia system, which is described below in the discussion of Lake Roosevelt.

Mid-Columbia TMDL Data

Data on the Mid-Columbia dams was collected by the US Army Corps of Engineers, the US Geological Survey, the US Bureau of Reclamation and the three Public Utility Districts. It includes both FMS data and near field studies. The U.S. Army Corps of Engineers and the U.S. Geological Survey collect FMS data jointly following rigorous quality control. Basic data quality procedures are provided in the annual Plan of Action (e.g., USACE, 2001b). Detailed methods and quality assurance data are reported by the U.S. Geological Survey (e.g., Tanner and Johnston, 2001). The Corps annual water quality reports provide detailed data quality analysis (e.g., USACE, 2000). The TDG data quality target for the FMS stations is a precision of no greater than 1% for paired readings.

The development of TMDL loading capacity and load allocations is based on data whose quality assurance/quality control procedures met or exceeded the standards applied by the Washington State Department of Ecology and the U.S. Environmental Protection Agency for their own data collection and analysis for TMDL development. Other data of less certain quality was used for background information, to aid in implementation, and other purposes.

The Fixed Monitoring Station (FMS) Data

The TDG data from the FMSs consisted of remotely monitored TDG pressure, dissolved oxygen, water temperature, and atmospheric pressure from a fixed location in the forebay and tailwater of each project. Data from the FMSs provide a long-term hourly record of TDG throughout the season, capturing detailed temporal and extreme events. However, the FMSs provide only limited spatial resolution of TDG distribution. In some cases, the TDG observed in the tailwater at the FMS location was not representative of average spillway conditions and misrepresented the TDG loading at a dam.

Spillway Performance Tests and Near-Field Studies

Spillway performance tests and near-field tailwater studies were conducted at several projects to define the relationship between spill operation and dissolved gas production more clearly. Water temperature, TDG, and dissolved oxygen were monitored in the immediate tailrace region, just downstream of the project stilling basin. These observations provided a means to relate the local TDG saturation to spill operations directly, and to define gas transfer in different regions of the tailrace area.

In these studies, automated sampling of TDG pressures in spillway discharges during uniform and standard spill patterns was conducted with an array of instruments in the stilling basin and tailwater channel of all the projects in the study area with the exception of Lower Granite. Automated sampling of TDG levels provide the opportunity to assess three-dimensional characteristics of the exchange of TDG immediately downstream of the stilling basin on a sampling interval ranging from five to 15 minutes. The integration of the distribution of flow and TDG pressure can yield estimates of the total mass loading associated with a given event. These tests were of short duration, generally lasting only several days and, therefore, pertain to the limited range of operations scheduled during testing.

In-Pool Transport and Dispersion Studies

During the 1996 spill season, in-pool transport and dispersion investigations were conducted to define the lateral mixing characteristics between hydropower and spillway releases. Water temperature, TDG levels, and dissolved oxygen were measured at several lateral transects located over an entire pool length. These studies focused on the lateral and longitudinal distribution of TDG throughout a pool during a period lasting from a few days to a week. In-pool transport and mixing studies were conducted below Little Goose, Lower Monumental, Ice Harbor, John Day, The Dalles, and Bonneville during the 1996 spill season. In most cases, a lateral transect of TDG instruments was located below the dam to establish the level of TDG entering the pool, with additional transects throughout the pool. These studies provided observations of the TDG saturation in project releases as they moved throughout an impoundment. However, only a limited range of operations was possible during the relatively short duration of these tests.

Operational Data

Operational data were obtained from each project detailing the spillway and powerhouse unit discharge on time intervals ranging from five minutes to one hour. The average hourly total spillway and generation releases, and forebay and tailwater pool elevations were summarized in the DGAS database. The tailwater pool gauge was generally located below the powerhouse of each dam. The tailwater elevation at the powerhouse was found to be within one foot of the water elevation downstream of the stilling basin in most instances.

Data Interpretation

The objective of this analysis was to develop mathematical relationships between observed TDG and operational parameters such as discharge, spill pattern, and tailwater channel depth for dams within the TMDL area. These relationships were derived with observations from the FMSs and spillway performance tests. However, before the analysis could be conducted, the monitored data had to be evaluated to determine its reliability for this kind of analysis. For example, the monitored TDG data from the FMSs provide a basis for defining the effects of spillway operation on dissolved gas levels in the river below a dam, but the following limitations should be noted:

- The FMSs sample water near-shore, which may not reflect average TDG levels of the spill. The monitor sites were, in general, located on the spillway side of the river to measure the effects of spillway operation. However, with a non-uniform spill distribution and geometry across the gates of the spillway, the FMS may be more representative of the spillbays closest to the shore. Outside spill bays without flow deflectors can create elevated TDG levels downstream from these bays compared to adjacent deflectored bays. A spill pattern that dictates higher unit discharges on these outside bays can further elevate the TDG levels downstream of these bays relative to the releases originating from the deflectored interior bays.

- Depending upon the lateral mixing characteristics, the FMS downstream of a project may be measuring spillway releases that have been diluted with hydropower releases. The tailwater FMSs below The Dalles and Bonneville are located in regions where substantial mixing has occurred between generation and spillway discharges. Under most conditions, the TDG saturation of generation releases is less than the TDG level associated with spillway releases. The TDG at the tailwater FMS will be a function of the discharge and level of TDG from both generation and spillway releases. Obviously, if there is no spill, then the monitored TDG levels will reflect the TDG saturation released by the hydropower facility.

- Passage of generation flows through a power plant does not significantly change the TDG levels associated with this water. However, there can be a significant near-field entrainment of powerhouse flow by spillway releases at some projects, especially if flow deflectors are present. Observed data suggest that, under these conditions, some portion of the powerhouse discharges will be subjected to the same processes that cause absorption of TDG by spillway releases. In these cases, the TDG levels measured immediately downstream of a spillway will be associated with the spillway release plus some component of the powerhouse discharge.

The observations of tailwater TDG pressure need to be paired up with project operations to conduct an evaluation of the data. A set of filters or criteria were established to select correctly-paired data for inclusion in this analysis. The travel time for project releases from the dam to the tailwater FMS was typically less than two hours and steady-state tailwater stage conditions were usually reached within this time period. Thus, the data records were filtered to include data pairs corresponding with constant operations of duration greater than two hours to exclude data corresponding with unsteady flow conditions. This filtering criterion eliminated data associated with changing operations and retained only a single observation for constant operating conditions equal to three hours in duration.

- *Manual and Automated Inspections for Obviously Inaccurate Observations.* An automated search for values above or below expected extremes identified potential erroneous and inaccurate data in the database. These data were inspected and, if appropriate, excised from the database.

- *Comparison of Measurements from Forebay and Tailwater Instruments During Non-Spill Periods.* During the non-spill periods, downstream measurements should approach the forebay concentration when only the hydropower project is releasing water. Inspection of the data was conducted to identify errors when this condition was not met.

- *Comparison of Measurements from Redundant Tailwater TDG Monitors, if Available.* TDG tailwater data was rejected when measurements of two instruments at the same site varied by more than 3% saturation.

Identification of Sources

There are seven sources of TDG within the geographic scope of this TMDL:

1. Grand Coulee Dam
2. Chief Joseph Dam
3. Wells Dam
4. Rocky Reach Dam
5. Rock Island Dam
6. Wanapum Dam
7. Priest Rapids Dam

Above Grand Coulee Dam there is a large contribution of TDG crossing the international border, and there is a contribution from the Spokane River. Sources upstream of the international border appear to include dams on the Columbia, Kootenai, and Pend Oreille rivers, both in Canada and the U.S. No other significant sources of elevated TDG exist in mainstem or tributaries of the Mid-Columbia River or Lake Roosevelt. Increases in TDG percent saturation can be caused by decreasing barometric pressure, increasing water temperature, or increased dissolved oxygen levels from aquatic biological activity.

Waters of the Columbia River flowing across the international border into Lake Roosevelt frequently exceed the TDG standard. This TMDL will establish a load allocation at the border based on what is needed to attain the TDG criteria in Lake Roosevelt. However since these are Canadian waters and outside the purview of U.S. regulation including the Clean Water Act, the U.S. has no direct authority over its attainment. Nonetheless, this allocation will provide a scientifically based goal that can be targeted during discussions and negotiations with Canadian sources. Such discussions currently occur on a regular basis. Furthermore there are dams upstream of Canadian waters, in the U.S., that are contributing sources of TDG, primarily on the Pend Oreille river system. Sources in U.S. waters, including those on the Spokane River, which discharges into Lake Roosevelt, will be addressed in subsequent TMDLs.

Earlier TMDLs issued for the Lower Columbia established the TDG load allocation for the Columbia River at the confluence of the Snake River (RM 325). This allocation was based on loading limitations needed in order to attain the TDG criteria in the Columbia River below this point. This allocation along with loading information contained in the Lower Snake TMDL will be utilized to establish the maximum allowable loading at the downstream boundary of the TMDL. The TMDL will be established such that the allocation will attain criteria throughout the reach and ensure criteria are also met in the lower river.

The information is provided to illustrate processes at the dams with their configuration at the time of the studies described. As structural modifications are made at the dams, the specific gas generation equations will change.

Lake Roosevelt

Description of Area

Lake Roosevelt is the impoundment of the Columbia River behind Grand Coulee Dam. At the high water mark the lake extends from the Canadian border downstream to Grand Coulee Dam, a distance of 148 river miles (Figure 2). Included in the impoundment is the backwater of the Spokane River, known as the "Spokane Arm" which extends approximately 29 miles upstream of the Spokane River's confluence with the Columbia.

Much of the land northwest of Lake Roosevelt is part of the Colville Indian Reservation. The reservation includes most of the lake for approximately 100 miles upstream of Grand Coulee Dam. The Spokane Indian Reservation is on the east side of the lake, for approximately ten miles upstream of the confluence of the Spokane River, and includes all of the Spokane Arm and a portion of Lake Roosevelt along its boundaries.

Water Quality Impairment

Lake Roosevelt was placed on Washington State's 303(d) list as impaired for total dissolved gas in both 1996 and 1998. Data collected at the Bureau of Reclamation's fixed monitoring station, downstream of the international border, shows that the numeric criterion for TDG is continuously exceeded from mid-April through mid-September in a typical year (Figure 5). It is not uncommon to have episodes of TDG exceeding the standard during high runoff events in the fall and winter as well. In six out of the eight years of data at this station TDG levels have remained above 120% for the entire month of June. Typically, recorded levels of TDG are higher at the international border station than any other fixed monitoring station (FMS) on the U.S. portion of the Columbia River from April through January each year.

The next FMS downstream is in the forebay of Grand Coulee Dam. Data from this station indicates total dissolved gas impairment remains a problem throughout the 148 miles of lake. Values recorded at Grand Coulee forebay are less than readings from the border but typically exceed 110% from early May through mid-August.

The sources of total dissolved gas to Lake Roosevelt are the flows across the international border and flow from the Spokane River. The Spokane River flows into Lake Roosevelt approximately 45 miles above Grand Coulee Dam. It is the largest tributary directly into Lake Roosevelt. High TDG levels have been recorded in the area above the Spokane Arm, which are related to operation of the 7 hydroelectric projects on the Spokane River. This TMDL will set an allocation in the Spokane Arm which will be utilized as a boundary condition in an upstream TMDL for TDG in the Spokane Basin.

Although there are sources of TDG coming into Lake Roosevelt from the Spokane River, the most significant sources of TDG influencing the Lake are upstream of the international border. These include sources in Canada on the Pend Oreille, Kootenai, and Columbia rivers and sources in the U.S. on the Pend Oreille River system. This TMDL will set an allocation at the international border, which will contribute to the formulation of a TMDL in the Pend Oreille River that Ecology is planning for 2004-2005.

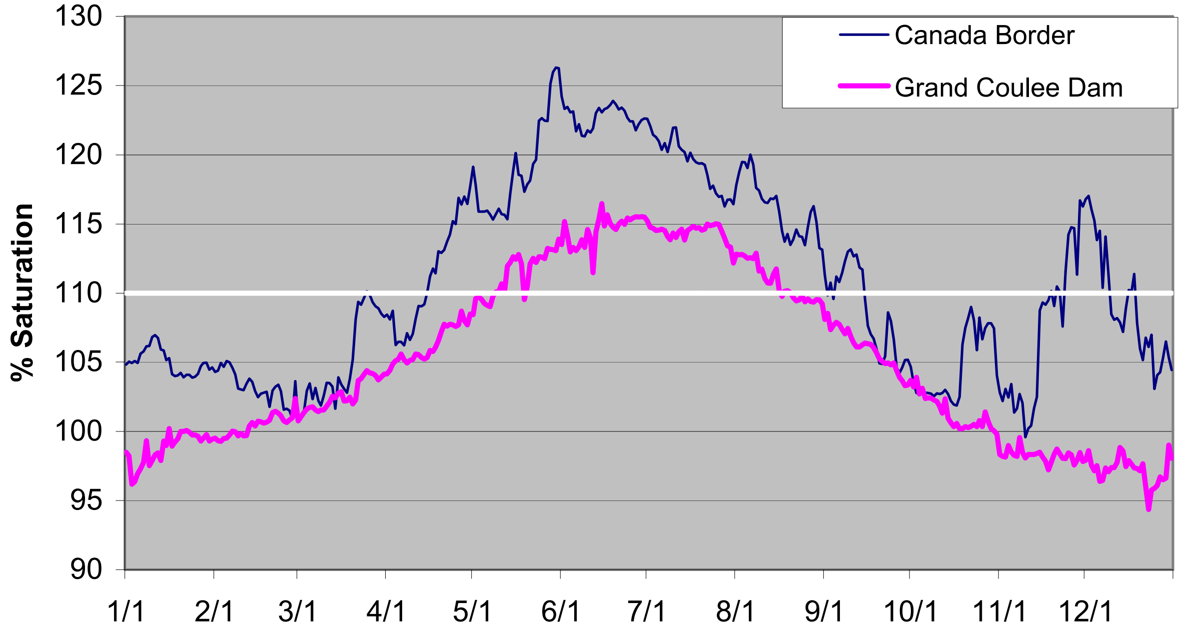

Figure 5: Average TDG Levels at International Border (1995-2003) and Grand Coulee Dam Forebay (1997-2003)

The sources in Canada and their influence on TDG levels in Lake Roosevelt will be discussed below. Although these sources are outside the U.S. and beyond the reach of the Clean Water Act, they are important in understanding the problems affecting Lake Roosevelt. The system immediately above the Canadian border is complicated by the interaction of three major river systems (Figure 6). All of these rivers have dams on them that are sources of TDG (Table 3). Canadian dam owners and government agencies have studied the transboundary area over the last ten years, in order to evaluate projects and operational measures to reduce TDG levels in the system. Some of these projects have been implemented and some are still in the planning phase.

This document will use the information collected in Canada and at the international border to describe the generation of TDG that precipitated the listings at the border, as well as the anticipated reductions from planned and implemented improvements. Additional measures that would be needed to bring about compliance with the 110% standard at the international border will also be discussed.

Table 3: Canadian Dams on the Columbia, Kootenai, and Pend Oreille Rivers

Name	River Mile	Year Built	Normal Max Head (ft.)	Hydro-electric Capacity (mw)	Hydraulic Capacity (cfs)	Avg. Annual River Q (cfs)	Owner	Drainage Area (sq.mi.)
Columbia River								
HughKeenleyside	780	1968	69	185	40,000	40,100	BC Hydro	14,100
Revelstoke	934	1983	425	1,740	56,000		BC Hydro	10,300
Mica	1018	1973	615	1,740	41,600	20,510	BC Hydro	8,100
Pend Oreille River								
Waneta	0.5	1954	205	420	28,300	27,820	Teck Cominco	26,000
Seven Mile	6	1979	197	605	39,000	26,800	BC Hydro	
Kootenai River								
Brilliant	1.9	1944	98	109	18,000	30,650	CPC/CBT	18,996
South Slocan	13.4	1928	72	54	10,500	27,570	Aquila	
Lower Bonnington	14.3	1897	66	41	9,500	27,570	Aquila	
Upper Bonnington	14.8	1907	71	60	13,500	27,570	Aquila	
Corra Linn	16.1	1932	58	41	12,600	27,570	Aquila	
Kootenay Canal		1975	245	528	26,000		BC Hydro	

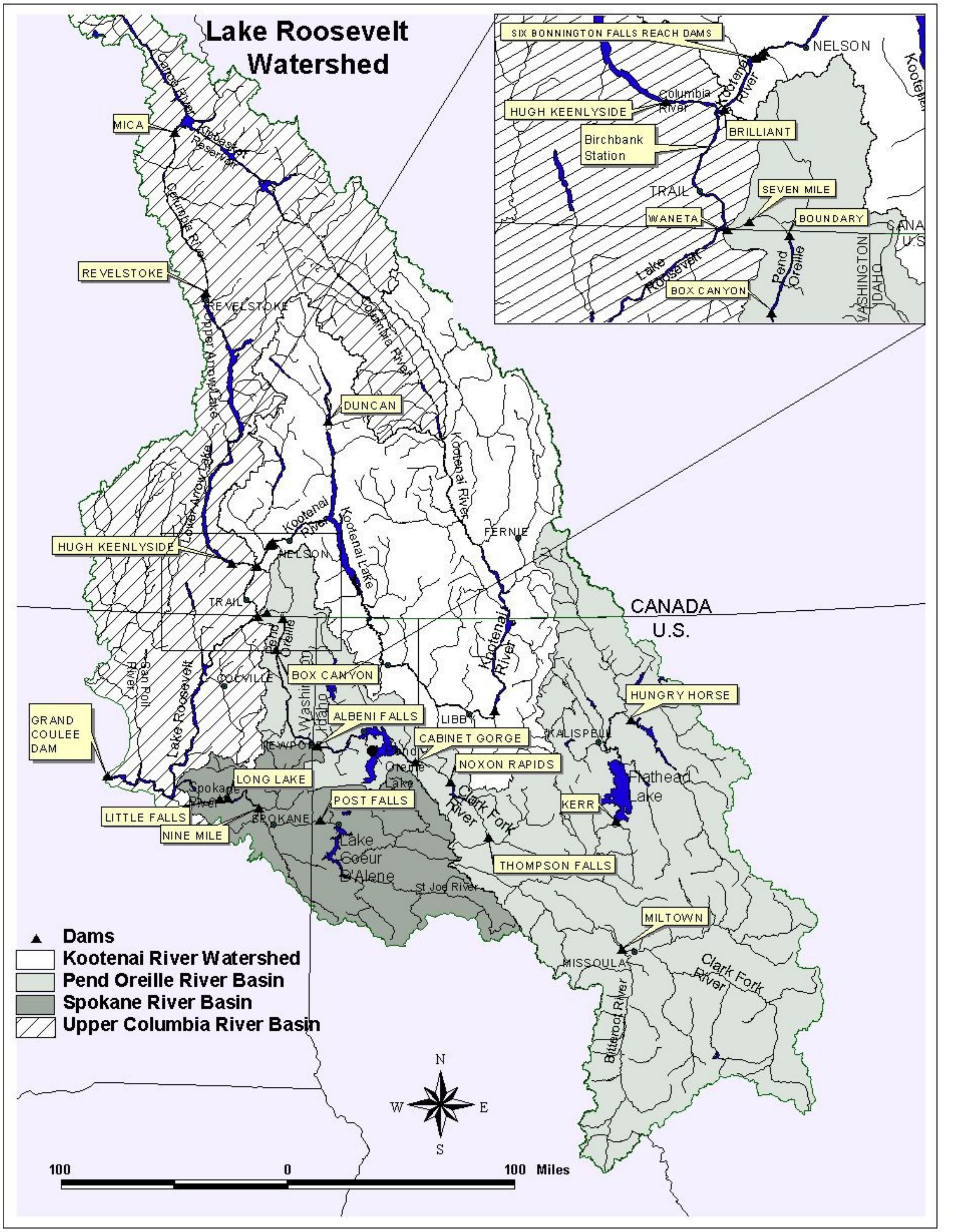

Figure 6: Lake Roosevelt Watershed

Canadian Modeling of TDG in Transboundary Columbia System

To assess the relative impacts of the sources of TDG and the effects of the river system's interaction on TDG levels and fish habitat the Canadian dam owners and governmental agencies commissioned the creation of a model of the system. The model was created by Aspen Sciences Limited. It is a mass balance model that uses empirical data on dam operation in conjunction with data collected at a variety of TDG monitoring stations.

This has enabled Canadian dam operators to predict the effects of operational changes in dam management and increases in power generation capacity on TDG levels. The model uses data that has been collected between 1991 and 2000 on the Columbia, Kootenai, and Pend Oreille rivers, mostly in Canada. The model is based on conservation of TDG and flow as described by the following equation:

$$\Delta P_{River} * Q_{River} = \Delta P_{Forebay} * Q_{Turbine} + \Delta P_{Spill} * Q_{Spill} + \Delta P_{Low\ Level\ Ports} * Q_{Low\ Level\ Ports}$$

where: ΔP = difference between TDG pressure and local barometric pressure
ΔP_{Spill} = Spillway ΔP
ΔP_{River} = ΔP at Monitoring Site(s) Downstream of Dam
Q_{River} = Total River Volumetric Flow
$\Delta P_{Forebay}$ = Forebay ΔP
$Q_{Turbine}$ = Total Turbine Volumetric Flow
Q_{Spill} = Total Spillway Volumetric Flow
$\Delta P_{Low\ Level\ Ports}$ = Low Level Ports ΔP
$Q_{Low\ Level\ Ports}$ = Total Volumetric Flow through Low Level Ports

Assumptions of the model:

Flow through turbines is not assumed to alter TDG levels.

The total flow of the river below a dam is equal to the sum of the flow over the spillway, the flow through the turbines and the flow through the low-level ports.
($Q_{River} = Q_{Turbine} + Q_{Spill} + Q_{Low\ Level\ Ports}$)

TDG is not assumed to dissipate except in three locations, where field data indicates a reduction in TDG levels:

- Flow going over Seven mile Dam on the Pend d'Oreille River
- Flow over the natural cascade spillway at South Slocan Dam on the Kootenai River
- The reach above Brilliant dam forebay

Increases in TDG levels at each dam is estimated for spill and operational conditions using regressions on data collected in the dam forebays and tail races between 1995 and 2000. For Hugh Keenleyside Dam and Brilliant there has been several years of data collected including near field studies of TDG increases under controlled operational conditions.

Sources of Impairment

Kootenai River

Current Conditions

The Kootenai River confluence with the Columbia is 28 river miles upstream of the international border. Its flow accounts for approximately 30% of the Columbia River annual flow at the international border. The headwaters of the Kootenai are in the Canadian Rockies near the Columbia River headwaters. The river crosses the border into the U.S., flowing about 200 miles through Montana and Idaho before re-crossing into Canada. Much of the lower portion of the river in Canada is a natural lake.

The seven hydroelectric projects located near the mouth of the river are all run of the river dams. Six of the seven projects are located between river mile 16 and 13. In the reach between the upper and lower of these six dams, the river drops 270 feet through a series of natural cataracts called Bonnington Falls. Most of the power projects located on this reach take advantage of the natural falls for additional spillway capacity. One project is located on a canal that bypasses the falls.

TDG was monitored in the forebay of the uppermost dam, Corra Linn, between April and November of 1999. TDG never exceeded the 110% criteria at this station. The next mainstem project upstream is Libby Dam, over 200 river miles away in Montana. Libby is the only storage dam on the Kootenai River.

Apart from the forebay station at Corra Linn, only short term TDG data has been collected in this reach. This limited data shows high gas levels, during spring runoff in the tail races of several of these dams. Values as high as 412 mm Hg delta pressure (155% saturation) have been recorded in this reach.

At the end of the Bonnington Falls section of the Kootenai River, TDG values are elevated in times of medium and high runoff. In the 11 miles between South Slocan dam tail race, at the lower portion of the Bonnington Falls area, and Brilliant Dam at river mile 1.9, levels of TDG decline. This decline is assumed to be due to dilution from the Slocan River tributary and dissipation in shallow riffle sections of the free flowing river. Nevertheless, TDG levels in the Brilliant forebay are often over the 110% criteria (See Figure 7 for TDG values recorded at Brilliant). Brilliant dam forebay and tail race have been the sites of seasonal TDG monitoring for several years. The Canadian TDG model predicts that Brilliant Dam forebay TDG levels exceed the criteria 70 days each year, although the model does not show a high correlation with the available data at this location.

Brilliant Dam has eight spillways and four turbines. Through the period of data collection (prior to 2001), the turbines had a total hydraulic capacity of 18,000 cfs. The average annual discharge at Brilliant is 30,650 cfs. Over 40% of the Kootenai River is spilled at Brilliant Dam in an average year. Increases in TDG in the Brilliant tailrace range from 60 to 100 mm Hg when spills over 7000 cfs occurred at the dam, see Figure 7. Modeling of the system indicated that Brilliant

Dam tail race is generally over the numeric criteria (110% saturation) a minimum of 150 days a year (42% of the year) and for nearly a third of this time exceeds 120% saturation.

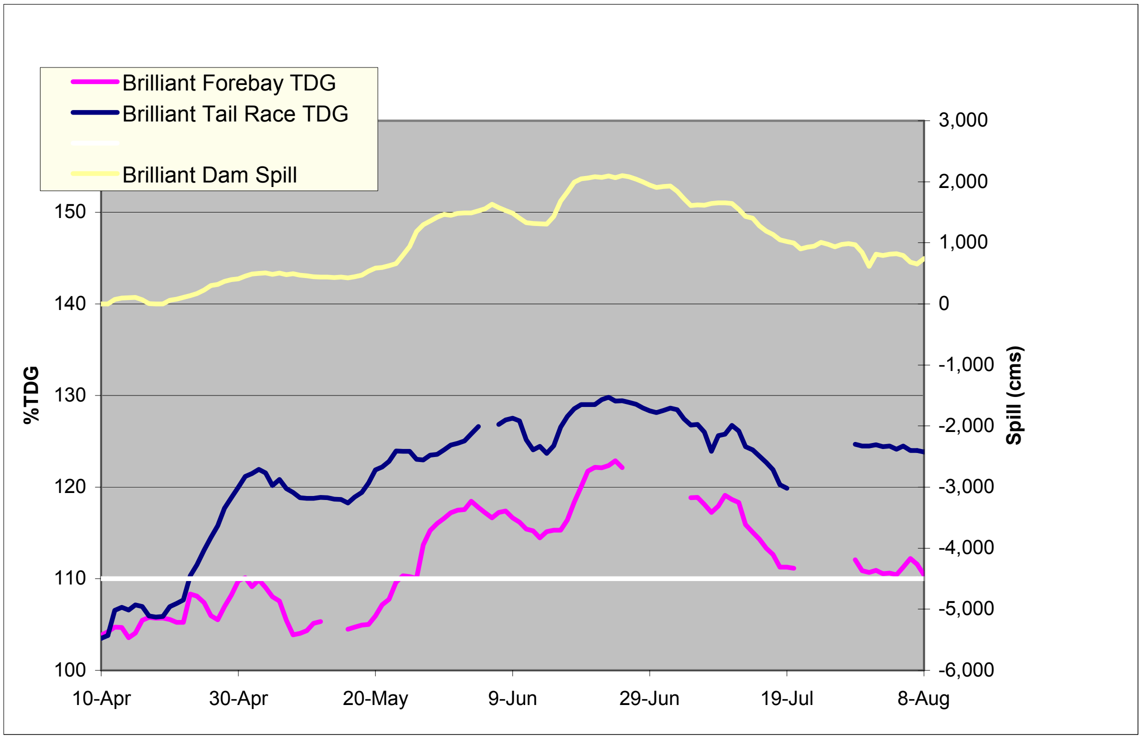

Figure 7: Brilliant Dam TDG in 1999

Improvements at Brilliant Dam

Near field operational studies were conducted at Brilliant Dam. In 2000 the dam owner agreed to use a spillgate operation plan that would reduce TDG levels downstream. In addition, projects to increase generating capacity by upgrading and increasing the capacity of the turbines have recently been completed at Brilliant. A further improvement is currently under contract that will lead to construction of an additional power plant on the eastside of the river. Part of the impetus behind this project is a desire to reduce TDG in the Columbia River.

Upgrade of the four turbines at Brilliant increased the hydraulic capacity through the power plant from 18,000 cfs to 21,560 cfs. This work was completed in the winter of 2002. Construction of an additional generating plant would further increase hydraulic capacity to 34,150 cfs. When completed these projects will reduce the amount of spill over Brilliant Dam and reduce TDG levels in the Columbia downstream of the confluence. The Canadian model estimates that these projects will reduce the number of days that the Brilliant tail race is over the 110% saturation criteria from 157 to 80, and reduce the number of days that tailrace levels exceed 120% saturation by 33 days. At the international border it is anticipated the Brilliant upgrade will reduce the number of days the 110 % criteria is exceeded by 18 and the annual number of days over 120% TDG saturation from 29 to 22 (estimates after completion of Arrow Lakes Generating station).

Reduction of TDG input at Brilliant Dam by additional power plant capacity will not address the problem of high TDG levels that are generated by dams in the Bonnington Falls reach. Flow through the power plants will pass elevated TDG water down stream without reduction. As Figure 7 indicates, the water coming into the forebay of Brilliant is typically over the 110% criteria 70 days a year, TDG generated by dams in the this reach remains an obstacle to meeting the standard at the international border.

Pend Oreille River

Current Conditions

The Pend Oreille River's confluence with the Columbia is immediately upstream of the international border. Its flow makes up approximately 28% of the Columbia River annual flow volume at the border and 10% of the total flow of the Columbia River. The headwaters of the Pend Oreille River are in the Rocky Mountains of Montana. The Bitterroot and Flathead rivers merge with the Clark Fork River in Montana. The Clark Fork flows north into Pend Oreille Lake in Idaho. At the lake's outlet the river is renamed the Pend Oreille River. It flows north through Washington State and enters Canada 16 miles before its confluence with the Columbia River.

There are two dams on the 16-mile-long Canadian segment of the Pend Oreille River: Waneta (immediately upstream of the confluence) and Seven Mile (at river mile six). Boundary Dam is located at river mile 16, just upstream of the border, in the US. Box Canyon Dam is 18 miles upstream from Boundary dam. These are the dams that most directly influence TDG levels in the transboundary Columbia, however there are several other major upstream dams on the Pend Oreille and its tributaries in the U.S. that elevate incoming TDG levels. The primary storage dam in the system is Hungry Horse, on the South Fork Flathead River, over 300 miles upstream of the Canada border.

Peak flow typically occurs in early to mid-June. The runoff season can begin anytime from mid-April to mid-May, often with a rapid increase in flow volume. The peak runoff season is typically over in early July, often with an equally precipitous decline in flow volume. Generally the peak of the Pend Oreille hydrograph coincides with the Kootenai River's peak flow in early to mid-June.

Less data on TDG has been collected in the Canadian Pend Oreille River system than in the Kootenai or the transboundary Columbia. The tail race of Waneta Dam is located in the confluence with the Columbia River. Turbulence and mixing effects have deterred collection of TDG data that would shed light on the increase in TDG from spill at Waneta Dam. It is acknowledged that the dam does cause elevated TDG levels during spill.

Several years of data have been collected at Seven Mile Dam. This data indicates that Seven Mile causes a reduction of TDG levels when it spills.

In 1999 data was collected in the Columbia River immediately upstream of the confluence of the Pend Oreille River. This data, in conjunction with the international border FMS station data, indicates that at high runoff on the Pend Oreille causes an average increase of 20 mm Hg TDG in the Columbia River at the international border. At low flow in the Pend Oreille, when no spill is occurring at Waneta, the Pend Oreille flow can reduce high TDG levels in the Columbia by approximately 20 mm Hg (7% to 10% saturation).

Seven Mile, Boundary, and Box Canyon dams have hydraulic capacities significantly higher than the average annual flow of the river. Waneta Dam spills over 10% of the river flow in an average year. TDG levels coming across the border into Canada during the spill season are often above the 110% criteria. Levels as high as 150% saturation have been recorded in the Boundary tail race. When Seven Mile Dam is spilling and the water coming in has TDG levels over the 110% criteria, spill over the dam tends to reduce TDG. Flows through the powerhouse at Seven Mile does not reduce gas levels. Figure 8 shows the levels of TDG at the border, the tail race of Boundary Dam and the forebay of Waneta dam in 2000.

Modeling of the Pend Oreille predicts that the tail race of Boundary Dam will exceed the 110% criteria 16% of the year (58 days) and above 130% saturation 11% of the year (40 days). Seven Mile Dam would reduce the percent of the year over 130% saturation to 2% (seven days) but would not change the number of days the standard was exceeded, according to the Canadian model. The correlation between the model and the empirical data is low for prediction of Waneta forebay TDG levels. The model indicates that spill at Waneta Dam contributes 11 days of exceedance over the 110% criteria and five days over 120% saturation to what would occur without any spill at this dam.

Planned Improvements

The upgrade of either three or all four of the turbines at Waneta Dam is currently under consideration. This would have the effect of reducing spill over the dam by increasing the hydraulic capacity from 25,000 cfs to either 29,800 or 31,300 cfs, as well as increasing the power output of the dam. Modeling of these upgrade proposals predicts a reduction of three to four days over the 110% criteria a year, and no change in days over 120% saturation. This low number is partially due to the high levels of TDG coming into the forebay of Waneta that result from TDG generation upstream in the U.S. The addition of a second power plant at Waneta is also under consideration, this would further decrease the amount of spill at that dam.

Pend Oreille/Clark Fork River Basin in U.S.

The Pend Oreille River only flows through Canada for the final 16 miles of its length, and the rest of the river runs from its headwaters in Montana through Idaho and Washington. Waters coming from the U.S. are often impaired in the spring, during high runoff. This is the most significant barrier remaining barrier in the way of Canadian waters attainment of the 110% standard at the international border. There are two hydroelectric dams in Washington (Boundary Dam, owned by Seattle City Light, and Box Canyon Dam, owned by Pend Oreille PUD), and one in Idaho downstream of Lake Pend Oreille (Albeni Falls Dam, owned by the Corps). There are several other dams upstream of Lake Pend Oreille in Idaho and Montana. The state of

Washington is planning to develop a TMDL addressing the impairment to its waters in 2004-2005.

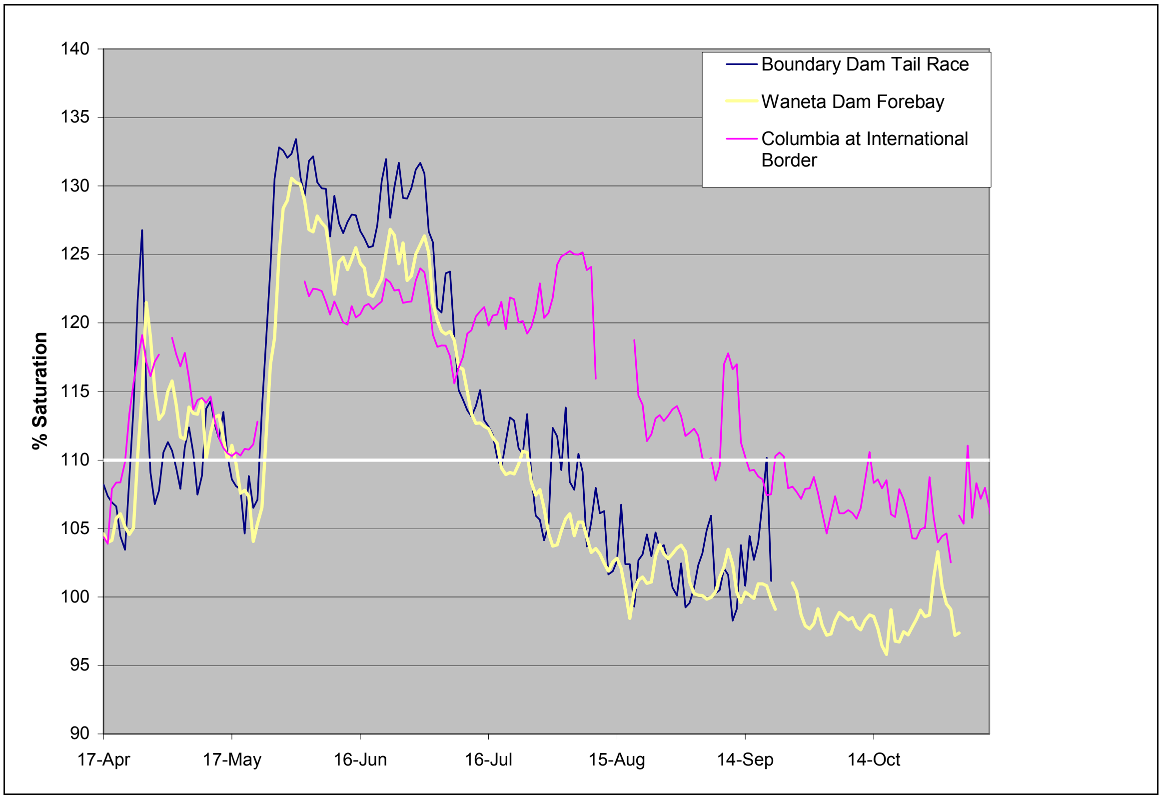

Figure 8: Pend Oreille and Columbia River TDG data from 2000

Columbia River

The Pend Oreille River's confluence with the Columbia is immediately upstream of the international border, and the Kootenai River enters twenty-eight river miles upstream. The Columbia, Pend Oreille, and Kootenai rivers have similar average annual flow volumes in this area (Figure 9). The complex interactions occurring in this reach will be discussed in the following section, as well as the contribution of dams on the Columbia River in Canada to TDG levels.

Hugh Keenleyside Dam

There are three dams on the Columbia River in Canada. Seven miles upstream of the Kootenai River confluence is Hugh Keenleyside Dam. Revelstoke Dam is 144 river miles upstream of Hugh Keenleyside. The intervening reach of the Columbia a large natural lake called Arrow Lake. Mica Dam is 84 miles upstream of Revelstoke. Hugh Keenleyside and Mica dams are major storage dams.

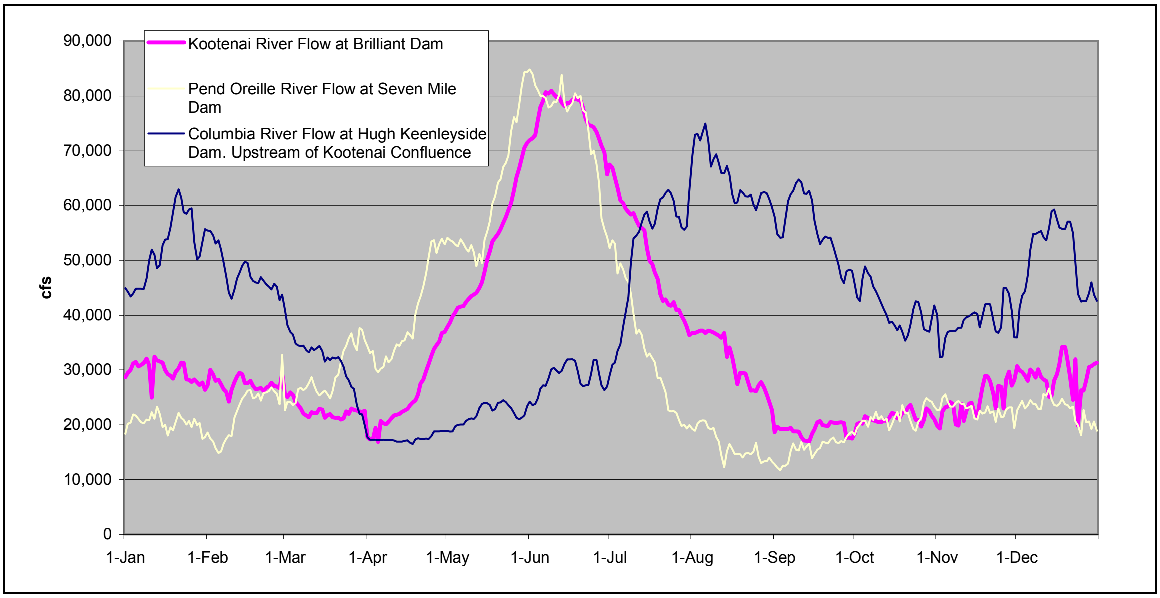

Figure 9: Average Flows in the Columbia, Pend Oreille, and Kootenai Rivers (1995-2000)

Hugh Keenleyside was constructed in 1968 under the Columbia River Treaty. It has four spillways and eight low-level ports. The low level ports are located four on either side of the central spillways. Hugh Keenleyside has no power generation capacity. Data collected from 1995 through 1999 shows that spill over Keenleyside dam dramatically increases TDG levels downstream in the Columbia. Figure 10 illustrates this pattern using average levels of recorded TDG (averaging years vary between sites). Flow through the north low level ports increases TDG only slightly, but flow through the south ports can add noticeable TDG to the flow, although not as significant as levels from spillway releases.

The maximum capacity of flow through the low level ports is a little over 88,000 cfs. But flow through the ports is constrained by a number of restrictions relating to the structural integrity of the dam. When high spill is occurring, usually at times of high head behind the dam, the flow through the low level ports is limited to approximately 28,000 cfs. The average annual flow volume in the Columbia at Hugh Keenleyside is 40,100 cfs.

Water coming into the forebay of Hugh Keenleyside is occasionally over the numeric standard for TDG in the spring. The next dam upstream on the Columbia is Revelstoke, 144 miles upstream. The intervening reach of the Columbia is a large natural lake, Arrow Lakes. Revelstoke is not a dam that elevates TDG significantly. The slightly elevated levels of TDG have been attributed to elevated temperatures in the Arrow Lakes.

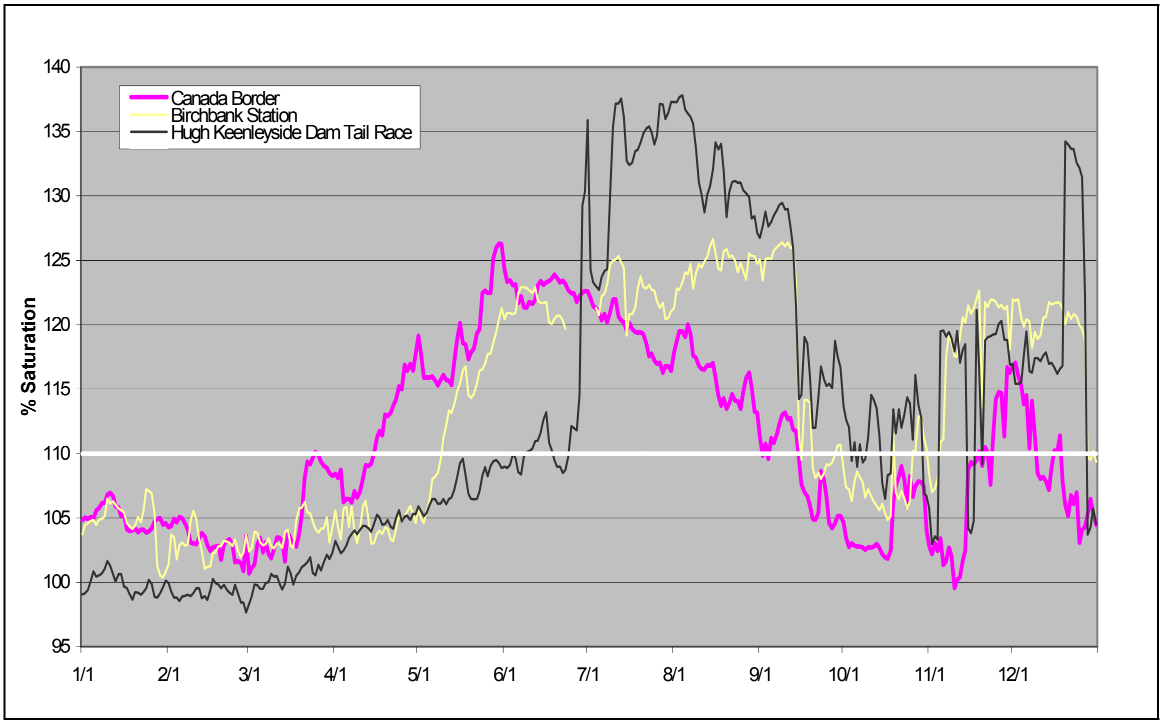

Figure 10: Average TDG Values in the Columbia River at and above the Canadian Border (Border 1995-2003; Birchbank 1995, 1999, 2000; Hugh Keenleyside 1995, 1997-2000)

During spill over Hugh Keenleyside increases of 250 mm Hg (30% saturation) are commonly measured at the station 1.5 miles below the dam. Values as high as 1020 mm Hg (140%) have frequently been recorded at this station. According to the Canadian TDG model the 110% saturation criteria is exceeded 40% of the year (146 days) on average at the station downstream of Hugh Keenleyside Dam, and levels are above 130% saturation for 29 days on average (8% of the year).

During the spill season at Hugh Keenleyside, TDG levels are reduced downstream, primarily by dilution from the Kootenai and Pend Oreille rivers, whose spill seasons are typically earlier in the year. Despite the downstream dilution these high levels of TDG are directly responsible for the TDG impairment at the international border from early July through the autumn.

Arrow Lakes Generating Station Improvement

The Arrow Lakes Generating Station has just been completed immediately below Hugh Keenleyside Dam. The plant was constructed to utilize the Columbia flow for power generation and in doing so reduce the need to spill at the dam and thus reduce TDG levels. The hydraulic capacity of the plant is approximately 40,000 cfs.

The Canadian model predicts a reduction from 35% to 28% (25 days) of the year over the 110% saturation criteria at the international border and a 3% (11 days) reduction in percent of the year over 120% saturation. Upstream the reduction is more dramatic with 13% of the year (47 days) expected to be brought below the 110% saturation criteria at Birchbank and 36 less days exceeding 120% saturation.

This past year has been the first season of operation for the plant. Monitoring that has occurred in the spill season below Hugh Keenleyside indicates a dramatic decrease in TDG levels below the dam, that appear to corroborate the model predictions for this reach.

Dynamics of the Columbia River System Upstream of Lake Roosevelt

In the 30 miles above the Canadian border, the Pend Oreille and Kootenai rivers flow into the mainstem Columbia River with flows similar to the Columbia at their confluence points. There are multiple TDG producing dams on all of these rivers and projects to reduce TDG levels at these dams. Unlike lower reaches of the Columbia the effects of these tributaries and the timing of runoff is important to understanding the levels of TDG downstream. This is the basic premise of the Canadian model of TDG.

The majority of the spill over Hugh Keenleyside Dam on the Columbia River begins in late June or early July and often continues through late September. There are often periods of spill in the winter as well. The runoff season on the Pend Oreille River begins anytime from mid-April to mid-May, often with a rapid increase in flow volume. The peak runoff season is typically over in early July, often with an equally precipitous decline in flow volume. The Kootenai River runoff season also begins in early to mid-May, with peak flows coinciding with the Pend Oreille's in early to mid-June. The Kootenai's hydrograph declines more slowly, although its season tends to be over by early August.

In the spring, when run off on the Kootenai and Pend Oreille is highest, Hugh Keenleyside is allowing its reservoir to fill and is generally not spilling. This staggering of flow has two effects on TDG impairment:

- a longer season of TDG levels exceeding the 110% standard; and
- reduced TDG levels, due to dilution by unsaturated flows.

Attainment of 110% Saturation at the International Border

As discussed above, Canadian dam owners are in the process of retrofitting a number of sites in the system with increased power generation facilities that are likely to have a significant beneficial effect on the TDG levels in the Columbia and Lake Roosevelt. These projects will reduce, but not eliminate, exceedances of TDG levels above 110% saturation levels at the border. This is primarily due to the high levels of TDG that originate in the U.S. on the Pend Oreille River system dams. It appears that retrofits to the U.S. dams on the Pend Oreille will be necessary to bring TDG levels within the numeric criteria at the border.

The primary barrier to reducing TDG levels originating in Canada are the high levels of TDG generated on the Kootenai River upstream of Brilliant dam in the Bonnington Falls reach. Although this is the largest Canadian source of TDG, additional reductions could be gained by further reductions at Waneta, Brilliant, and Hugh Keenleyside dams as well as upstream dams on the Columbia.

Projects that could be undertaken in Canada to bring the river closer to 110% saturation are listed below. There has not been sufficient study of the dams in the system to determine the magnitude of reductions that could be expected from these measures.

- Installation of flow deflectors
- Near field studies of the major system dams that would evaluate the contribution of tailrace depth, and entrainment of power house/low level port flows, spill pattern and allow more precision in selecting effective retrofits and operation plans.

Spokane River

The only source of total dissolved gas into Lake Roosevelt below the international border is the Spokane River. The Spokane River flows into Lake Roosevelt approximately 45 miles above Grand Coulee Dam. It makes up 9% of the Columbia's flow at the confluence. There are seven dams on the Spokane River, six of which are owned by Avista. Data collected from 1999 through 2001 by Avista, indicates that TDG levels exceed the 110% criteria in the tail race of Little Falls dam, just above the Spokane Arm.

Gas levels measured below Little Falls Dam between 1999 and 2001 exceed 110% saturation from mid- to late March until mid June or early July each year. For at least a month each year TDG levels were above 120% saturation and levels as high as 134% were measured. Although the average annual flow of the Spokane is small in comparison with the Columbia it peaks earlier and the average monthly flow for the Spokane in April makes up over 22% of the Columbia flow (Figure 11).

A comparison of data from the FMS stations at the international border and Grand Coulee forebay, with data taken in the Little Falls tail race does not indicate that Spokane River TDG levels significantly influence levels downstream in the Columbia. The only period of time that shows a potential influence is from late March through early April, when TDG level in the Grand Coulee Forebay are slightly elevated above the levels at the international border, and high levels are recorded in the Little Falls tail race (Figure 12). None of the data from these years show Spokane River contributions elevating TDG above the 110 standard and the increases noticed are very minor at Grand Coulee Dam.

Elevated TDG below Little Falls dam appears to have a significant effect on the Spokane Arm, although there are only a few data points from the Spokane Tribe's Limnology project to document these effects.

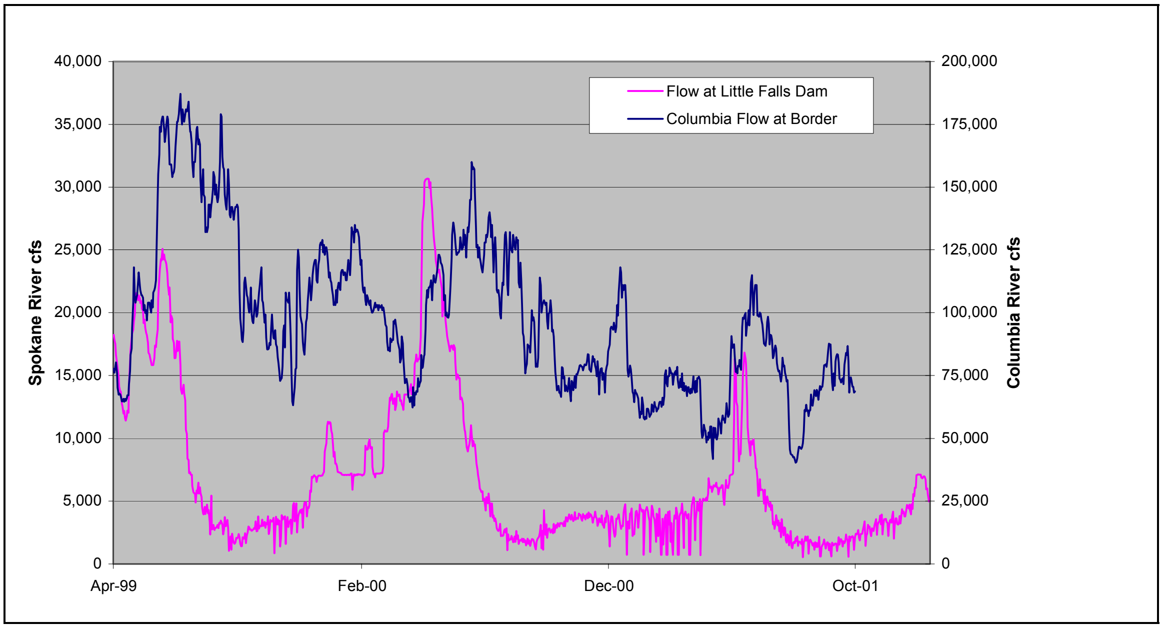

Figure 11: Flow in the Spokane River and Columbia River (International Border)

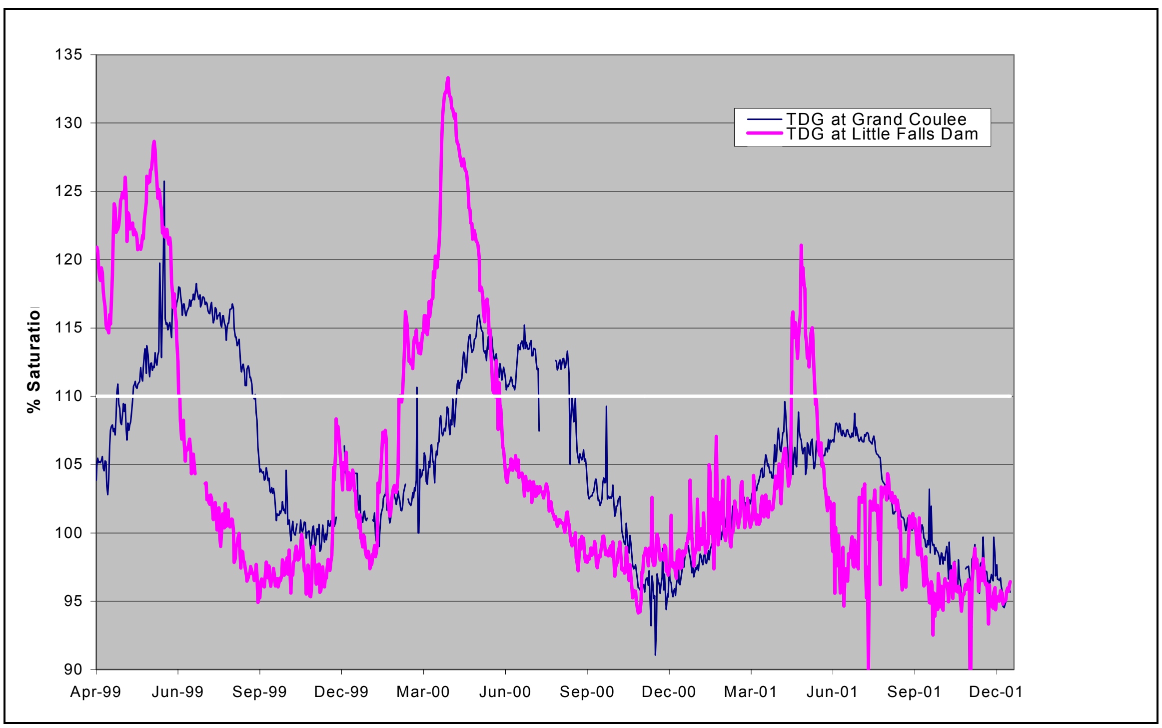

Figure 12: TDG at Little Falls Dam and Grand Coulee Dam Forebay

Ecology is developing a TMDL for TDG in the Spokane Basin in 2003-2004. The Spokane River TDG TMDL at its downstream end will address reductions necessary to attain the allocation derived for the Spokane River as presented in this TDG TMDL.

Influence of Ambient Conditions

Lake Roosevelt has a residence time of a week to several months. The median residence time is 5 weeks, and the 5th and 95th percentiles range from 2 to 10 weeks. Therefore, TDG entering from Canada has ample opportunity to be influenced by ambient influences such as turbulence and mixing, changes in water temperature and barometric pressure, and wind.

When dissolved gas is supersaturated compared to the atmosphere, the system seeks equilibrium by gas exchange from the water to the air. Since Lake Roosevelt is fairly deep, the surface to volume ratio is low and gas exchange is slow. Nonetheless, the general tendency will be for TDG levels to decrease. Wind can increase gas exchange by causing mixing in the surface layers and increased surface area from waves and “white-caps”. A variety of empirical models have been developed to predict gas exchange as a function of wind speed (see Cole and Wells, [2001] for a review of these equations). However, the physical process is too variable and dependent on environmental conditions to be deterministically modeled. A wind-gas exchange curve usually has to be calibrated to fit observed data through modeling.

An increase in water temperature or decrease in barometric pressure can cause an increase in TDG percent saturation without any change in the mass of dissolved gas. Therefore, for any given gas pressure crossing the border, TDG levels are likely to rise and fall as they move through Lake Roosevelt simply because of changes in these two parameters. Therefore an ideal target for TDG would be somewhat less than 110% saturation to allow a margin of safety for gas levels to increase due to changes in ambient conditions.

Another possible influence is primary productivity. In the late spring and early summer algal oxygen production can raise TDG levels by several percentage points. Therefore hot, still, sunny conditions will optimize conditions that can result in increased TDG levels. Conversely, cool, windy, cloudy days will produce the greatest decreases in TDG.

The long residence time of Lake Roosevelt and the complexity and variability of interactions between these parameters make it very difficult to predict the magnitude and frequency of TDG increases from changing ambient conditions. An accurate and well-calibrated model would be the best way to assess changes in TDG in Lake Roosevelt away from the fixed monitoring stations. However, no existing model has been developed and calibrated for TDG in Lake Roosevelt, and such an effort is beyond the scope of this TMDL. The need for improved modeling of Lake Roosevelt may provide a future opportunity to evaluate TDG dynamics in the lake in greater detail.

1. Grand Coulee Dam

Project Description

Grand Coulee dam, owned and operated by the U.S. Bureau of Reclamation, is a complex project with multiple structures (Figure D-1). It has three powerhouses: the original two – right and left – are aligned with the spillway, while the third powerhouse, added in the 1960's, sits at a slight angle on the east bank. The Pump-Generating Plant connected to Banks Lake is located on the west bank of the forebay.

The spillway consists of 11 drum gates at the top of the dam, controlling spill from the crest at an elevation above mean sea level (El.) of 1260 feet to the maximum water surface of El. 1290. There are also 20 outlet works conduits (two rows of ten) that allow spill when the impoundment is below the spillway crest. The centerlines of the upper and middle outlets are El. 1137 and 1037 respectively. (Lower outlets were used for construction but are now sealed shut.) The outlet works can pass 192 kcfs at full pool and the spillways have a combined capacity of 1,000 kcfs. The spillway has a submerged roller-bucket energy dissipater at El. 874.4 and discharges onto the rock surface downstream. The total hydraulic height of the dam is 350 feet.

The three powerhouses have a combined capacity of 280 kcfs, which allows them to pass the entire river's flow up to the 7Q10 flood flow. The centerline for the right and left powerhouse intakes are at El. 1041, while the centerline for the third powerhouse intake is El. 1130. The Pump-Generating Plant consists of six pumps and six pump-generators. The intake is at El. 1193. Water is pumped into Banks Lake, which is the upstream end of the Columbia Basin Irrigation Project. Water can be released from Banks Lake back through the pump-generators for peak power demand.

When Grand Coulee Dam was constructed no fish passage facilities were provided. Therefore, it blocks access for anadromous fish to all spawning areas upstream.

Grand Coulee Dam is sometimes termed "the faucet" of the Columbia River. It is the furthest downstream storage reservoir, and has the capacity to store or release virtually any flows. Operation of Grand Coulee dam is regulated by a variety of concerns, with flood control and power generation needs at the forefront, followed by fish passage flow requirements. Once water is released from Grand Coulee to meet flood storage or peak power needs, the ten downstream reservoirs have little choice but to pass those flows through.

TDG Generation Processes

Frizell (1996) conducted an analysis of historical gas measurements to evaluate gas production from Grand Coulee dam. Research in the 1970's evaluated total dissolved nitrogen, the primary constituent of TDG. When high TDG levels were observed entering Lake Roosevelt at the Canadian border, they showed up in the Grand Coulee forebay with very little change. Frizell (1998) notes that:

> …only limited surface degassing occurs as water travels the 150 miles from the international boundary to Grand Coulee Dam. Although Grand Coulee power plant releases do not increase downstream dissolved gas levels, releases from the dam consistently exceed the 110% dissolved gas standard between May and August of most years, even with no spill, because of high gas levels in the Coulee forebay. Operation of Grand Coulee Dam further increases the already high forebay TDG levels during periods when spill releases, which bypass hydropower facilities, are discharged through the outlet works or the spillway drum gates.

USBR conducted testing in March 1997 of TDG generation from combinations of the powerhouse and outlet works (Frizell, 1997a; 1997b; Frizell and Vermeyen, 1997). Five tests were conducted that explored combinations of upper and lower outlet works conduits and powerhouse discharges. Three tests were run with upper outlet conduits discharging at around 32 kcfs and power plant flows of 0, 31, and 66 kcfs. Two tests looked at outlet works discharges from the lower conduits alone, and combined upper and lower conduits, both with no powerhouse flows. TDG measurements were taken downstream of the dam at 2.3 miles, 6.6 miles (FMS station) and 15 miles (fish pens). Initial reconnaissance showed that powerhouse and spill flows were mixed by the 2.3 mile station (at flows of roughly 100 kcfs), but were not fully mixed at locations closer to the dam.

Forebay TDG values were under 110% during the tests. TDG levels exceeded 140% saturation when either the upper or lower conduits were operated alone with no powerhouse flows. When the upper and lower conduits were operated together, TDG levels were relatively lower, but still exceeded 130% saturation. Increased powerhouse flows produced lower TDG levels, mostly through dilution. TDG levels were highest at 2.3 miles downstream and decreased with the downstream distance.

Interpretation of results from these tests is limited due to the narrow range of flows under which they were conducted and the limited number of measurements and sample locations. However the tests did demonstrate the high level of gas generated by use of the outlet works. The report recommended operating paired high and low conduits if use of the outlet works was necessary.

Extremely high spring run-off in 1997 caused TDG levels in excess of 130%, resulting in high fish mortality both in wild resident fish and fish in aquaculture operations in Lake Rufus Woods (AquaTechnics, 1998). Researchers were able to document that the highest TDG levels resulted from operation of the outlet works, which were being operated to create storage in Lake Roosevelt for flood flows. Operation of the drum gate spillway produced relatively lower TDG levels.

The AquaTechnics report made a number of recommendations:

- Operations should be modified to minimize the use of outlet works for spills.
- Acutely lethal spikes of TDG were attributed to the rigid adherence to "rule curves" that produce rapid variations in outlet works releases. They recommended some modification of the rule curve to avoid high magnitude peaks and operate for steady spill rates.
- In general, operations should be reevaluated to include the minimization of TDG levels.
- Further evaluations were recommended of existing monitoring and of the TDG generation processes for various spill and power generation operations.

Schneider (1999) evaluated TDG production at Grand Coulee from previous studies and FMS data. Using data from 1996 and 1997, this study developed TDG exchange equations for outlet works and drum gate operations. The evaluation of outlet works releases assumed that TDG loading is directly proportional to the spillway discharge. The statistical evaluation found a fairly strong linear relationship (r^2>0.9), and indicated that powerhouse flows were entrained into the spillway. The analysis of drum gate spills assumed that TDG loading is an exponential function of unit spillway discharge (average discharge per spill bay). The relationship found was slightly weaker (r^2>0.8), with a slight indication of entrainment. In general, for the same spill volume TDG loading from drum gate releases was less than 60% of TDG loading from outlet works releases.

This study was very limited in scope, since it relied on existing data. It concludes that additional data collection and analysis is needed to assess TDG generation in more detail, specifically in the following areas:

- The effect of various modes of operation with regard to spill patterns;
- The amount of powerhouse flow entrainment and conditions causing increased entrainment;
- Near-field (forebay and tailwater) TDG gradients, exchange, and mixing processes.

Both Frizell (1998) and Schneider (1999) raise concerns about the quality of forebay TDG data. Evaluation of the date suggests that thermal stratification sometimes occurs in the forebay, which produces different TDG levels at different depths. In addition, differences in powerhouse depth can selectively affect which depth TDG is drawn from and can pull in upstream TDG at that depth, causing even greater vertical variability in TDG. Additional research was suggested to better understand TDG patterns and processes under stratified conditions in the forebay.

2. Chief Joseph Dam

Project Description

Chief Joseph Dam, owned by the U.S. Army Corps of Engineers and operated out of the Corps Seattle office, is the Corps' largest power-producing dam. The dam is over a mile long and spans the Columbia River near Bridgeport above the Okanogan River (Figure D-2). The powerhouse contains 27 turbines with a hydraulic capacity of 219 kcfs, and is angled at 90^o from the spillway structure. The spillway has a total length of 980 feet, with 19 radial gate-controlled bays each 36 feet in width. The elevation of the spillway crest is 901.5 feet, and the operating pool of Lake Rufus Woods (the impoundment behind the dam) ranges from 950 to 956 feet. The maximum total spillway design capacity is 1,200 kcfs. The spillway currently has no deflectors installed.

The tailwater elevation ranges from 780 to 790 feet, and typical depths on the stilling basin apron are 36-42 feet. The stilling basin is 167 feet long and ends with baffle blocks and stepped end sill about 11 feet in height. Downstream of the end sill the channel bed elevation ranges from 725 to 755 feet elevation.

Chief Joseph Dam is the farthest downstream barrier to anadromous fish passage on the mainstem Columbia River. Due to the existing blockage at Grand Coulee Dam and the limited habitat available below Grand Coulee, fish passage facilities were deemed unnecessary.

TDG Generation Processes

The Corps conducted an intensive TDG field study at Chief Joseph Dam on June 6 through 11, 1999 (Schneider and Carroll, 1999). Twenty-five meters were deployed to record TDG, temperature, and other parameters at 15-minute intervals in the Chief Joseph forebay, tailrace, along several transects in the downstream pool (Lake Pateros), and in the Wells Dam forebay. TDG was also measured manually in the Methow and Okanogan rivers. Velocity was measured below the dam with Acoustic Doppler Current Profiling equipment. During the study the dam operated under a series of varying spill volumes and configurations to evaluate different specific spill levels, percent spill conditions, tailwater elevations, and powerhouse operation configurations.

TDG levels were found to be fairly constant laterally across the forebay. TDG levels exiting the power house were unchanged from forebay levels. At the meter in the powerhouse outlet closest to the spillway higher TDG was observed, most likely from spill flows encroaching on turbine releases, or from recirculation of high TDG from spills.

Measurements at Transect 1, closest to the spillway, showed TDG levels from 125% to 142%, with measurements as high at 175% from a single meter placed closest to the south spill bay. For a standard spill (similar spill from all bays) the highest TDG levels were found in the center of the channel. When spills occurred from the south half of the spillway, the highest levels were observed at the southern end. The spill using the south half tended to recirculate water to the north end of the spillway, shown by elevated TDG at that location.

The potential for powerhouse entrainment to add to TDG loading was evaluated both by direct measurement and by calculations. Powerhouse operations were varied by running alternately the west half of the powerhouse and the east half of the powerhouse under similar spill configurations. No significant difference in TDG levels downstream was observed. When observed TDG levels were predicted with a mass balance model, calculated values matched observed fairly well. Both analyses suggest that the entrainment of powerhouse flows into the aerated spill resulting in increased TDG loading is negligible.

Transect 2, crossing the channel at the FMS station, showed that spillway and powerhouse flows were not mixed at this location. TDG levels at southwest side of the channel closely resembled forebay levels, indicating the presence of unmixed powerhouse flows. TDG at the northeast side, which includes the FMS station, were highest, indicating the presence of spillway flows unmixed or only partially mixed. Some TDG degassing below Transect 1 is also suggested by the lower levels at Transect 2.

A flow-weighted average of TDG at Transect 2 was calculated to determine an empirical model for the average TDG production from standard spillway releases. TDG generation was found to be an exponential function of unit spill way discharge. Partial spill patterns generated higher TDG levels for given unit spillway discharges as compared to a standard spill.

As TDG plumes from spill events moved downstream, they tended to mix across the channel, but were also affected in the Brewster Flats area by channel variability and inflow of the Okanogan River. At the forebay of Wells Dam TDG was fairly consistent across the channel. TDG generally took between 18 to 20 hours to reach Wells Dam from Chief Joseph Dam. Flow-weighted mass balance calculations of TDG indicated that very little degassing occurred in Lake Pateros below the Chief Joseph Dam tailrace during the study, which took place mostly during low wind conditions. Cooler, low-TDG inflows from the Okanogan and Methow rivers tended to lower TDG saturation at Wells Dam through dilution.

3. Wells Dam

Project Description

Wells Dam is owned and operated by Douglas Public Utility District and is located between the Methow and Chelan rivers. It is the only dam on the Columbia River with a “hydrocombine” structure (Figure D-3). This design integrates the spillway and powerhouse into a single structure. Each spillway bay is stacked on top of and between each powerhouse bay. Turbines are contained in individual silos. As a result, the powerhouse draft tube discharges are directly below the foot of the spillway.

The Wells Dam hydrocombine structure is 1,130 feet wide and contains 10 generating units. The overall dam length is 4,460 feet and the maximum gross head is 78 feet. The total hydraulic capacity of the generators is 220 kcfs, and the maximum spillway design capacity is 1,180 kcfs. The spillway consists of 11 vertical gates with upper and lower leafs. The spillways crest is 5½ feet above normal tailwater, and is below the tailwater during high flows. Even-numbered spillway entrances have been modified to constrict flow for fish attraction. Because of its design, Wells Dam has been the most successful of Columbia and Snake River dams in meeting downstream fish passage goals.

TDG Generation Processes

Wells Dam has not been the object of a detailed TDG generation study such as has occurred on most of the other Columbia River dams. Therefore little is know about its TDG generation processes. However, a general sense of its TDG generation characteristics can be inferred from the FMS record.

The TDG continuous monitoring record at Wells is relatively short, and begins later than the high TDG years of 1996 and 1997. The year 2002 was examined, since it was characterized by periods of high flow and spills at Columbia River dams, combined with periods of low power demand. The daily average TDG value for the forebay monitoring station was subtracted from the tailwater value for the same day, and the calculated increase plotted against the reported spill volume. Figure 13 shows that relationship.

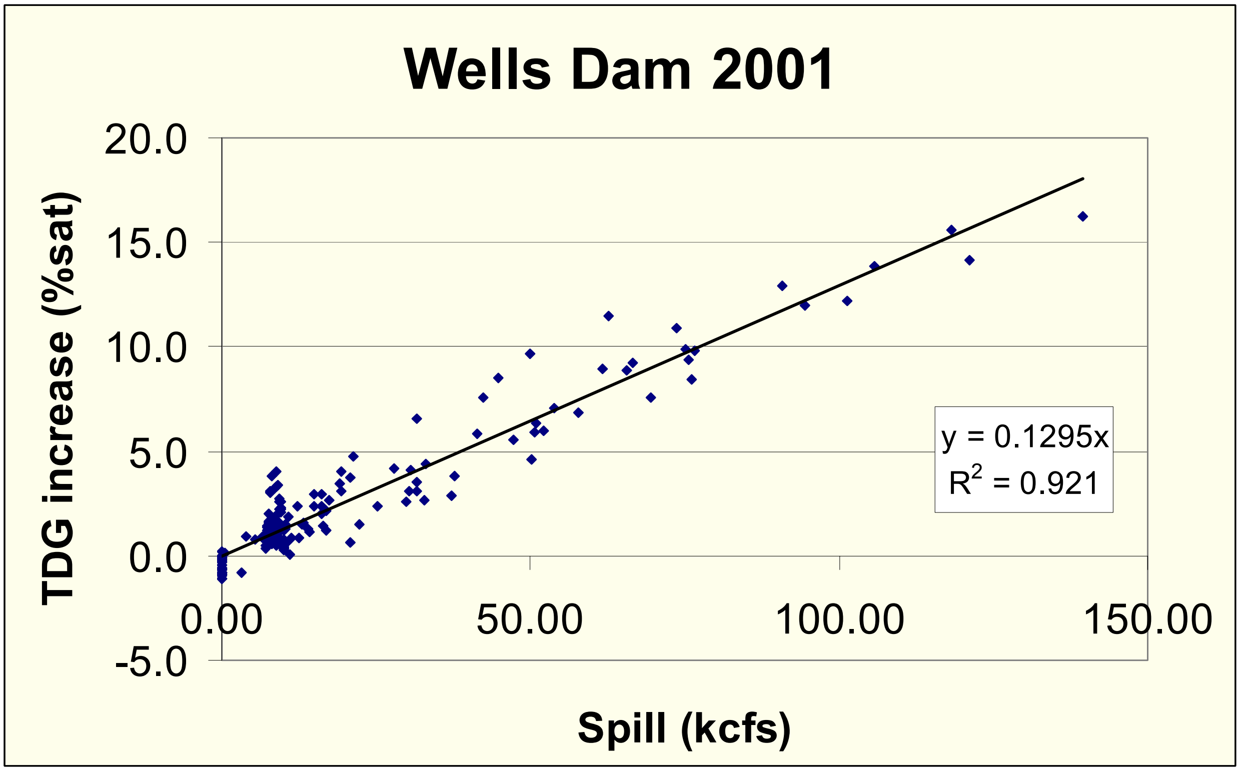

Figure 13: Wells Dam TDG Increases from Forebay to Tailwater FMS Monitoring Stations

This simple analysis shows a linear relationship of spill to TDG generation. Columbia River dams with separate spillways typically show an exponential relationship to unit spillway discharge. A detailed study would be needed to determine the effect of unit spillway discharge, powerhouse entrainment, tailwater depth, and other factors.

Ecology conducted two field surveys for TDG at Wells Dam in 2002 (Pickett, 2002). Only limited results were obtained, but slight lateral variation was observed in data across the channel. Possible causes include non-uniform spill configurations and differences if velocity patterns with depth and laterally across the channel. The lack of information on hydraulics in the Wells Dam tailrace limits the ability to understand the effect of flow characteristics on TDG levels.

4. Rocky Reach Dam

Project Description

Rocky Reach Dam (Figure D-4) is owned and operated by Chelan Public Utility District and is located just north of Wenatchee. The forebay elevation varies from 703 to 707 feet, while the tailwater elevation is normally 619 feet and varies with river flows. The spillway, which crosses the channel, has a crest elevation of 650 feet, a total length of 740 feet and consists of 12 bays, each controlled by a 56 foot radial gate. The powerhouse sits at about a right angle to the spillway, parallel to the shore. It is 1,090 feet long, contains 11 turbines, and has a hydraulic capacity of 220 kcfs.

The spillways and tailrace at Rocky Reach Dam have some unusual characteristics for a Columbia River dam. Each spill bay (except number 1) has a notched nappe deflector, which has the effect of forcing the edges of the flow together into the center. The stilling basin has several structures for energy dissipation, including aeration wedges, baffle blocks, and a notched sloping end sill. The purpose of these structures is to dissipate energy by creating very turbulent conditions in the shallow stilling basin.

The average stilling basin bottom elevation is around 595 feet. Tailrace bottom elevations mostly vary from 580 to 600 feet, with a few holes dropping to 570 feet elevation.

TDG Generation Processes

Typically the height of the spillway, the angle that the spill strikes the stilling basin, the depth of the tailwater, and the volume of spill will determine how much TDG its spill will generate. Because of the configuration of Rocky Reach's spillway, it has been considered a generator of relatively low levels of TDG.

Chelan PUD did a limited assessment of TDG production during in the 1999 season (Perleberg and McDonald, 1999). A fairly weak relationship was found between the increase in TDG from forebay to tailrace at Rocky Reach Dam and spill volumes, both as total discharge and percent of river flow. The change in TDG from forebay to tailrace averaged around 2% saturation with maximum increases of 12 to 15% saturation. Transect measurements showed a trend towards decreasing TDG levels laterally from east to west across the channel.

To better understand TDG production processes and the fate of TDG below Rocky Reach Dam, Chelan PUD contracted with the Corps to conduct a detailed study (USACE, 2003a). Transects of meters were placed just below the stilling basin, at two locations 1600 feet and 3700 feet below the dam, and near the tailwater FMS monitoring location at the Highway 97 bridge about 4.4 miles downstream. Monitoring occurred from April 26 through May 3, 2002.

Spills were varied both in amount and in configuration during the study. Spillway discharge varied from 10.6 to 61.0 kcfs, while spill patterns included standard, uniform over 11 of 12 bays, and uniform over 4 bays closest to the powerhouse, in the center, or farthest from the powerhouse.

Maximum TDG levels observed were over 128% saturation immediately downstream of the spillway and farthest from the powerhouse. Forebay levels at this time were around 108% saturation. The increase in average TDG from forebay levels ranged from 1.6 to 8.6% saturation. TDG generation at Rocky Reach Dam, without spill deflectors or other gas abatement structures, was comparable to other Columbia and Snake River dams with deflectors.

TDG saturation exiting the spillway was found to be a function of spill pattern, discharge, and also influenced by powerhouse operations. TDG generation followed a linear relationship to spillway discharge, and that relationship varied by spill pattern. The lowest TDG levels resulted from a uniform spill over 11 of 12 spill bays, both near the spill way and downstream. Spilling from 4 bays farthest from the powerhouse produced the highest TDG levels near the spillway, but average conditions downstream were similar to the standard spill. Spilling from the bays closest to the powerhouse produced higher average TDG downstream.

The hydraulics of the powerhouse flows and how they interacted with spill flows had a strong effect on TDG levels and spatial distribution below Rocky Reach. Throughout the river downstream, TDG remain highest on the east bank and lowest on the west bank closest to the powerhouse, reflecting incomplete mixing of powerhouse flows (with TDG at lower forebay levels) with spill flows.

Entrainment of powerhouse flows into spill flows was observed in the field and also identified through TDG mass balance calculations. Higher powerhouse flows appeared to decrease TDG generation, which could be related to tailwater elevation and depth of flow. Shifting power generation to the southern turbines (farthest from the spillway) also appears to help reduce TDG generation.

5. Rock Island Dam

Project Description

Rock Island Dam is owned and operated by Chelan PUD, and is located just south of Wenatchee (Figure D-5). It was the first dam constructed on the Columbia River. The minimum pool elevation is 609 feet above sea level, and normal tailwater elevation is 577 feet. Total head is relatively small (35-40 feet) for Columbia River dams. The total dam structure is 3,800 feet long and consists of a spillway in the center flanked by two powerhouses. The structure as a whole is relatively complex, since it was constructed on natural basalt outcroppings and has been built in three separate construction phases.

The First Powerhouse extends 746 feet from the east bank, while the Second Powerhouse on the west side of the channel is 470 feet long. The combined hydraulic capacity of the powerhouses is 220 kcfs. The spill way is slightly curved on its west end, and consists of 32 vertical gates. The six east gates (1-6) and seven west gates (26-32) have deep sills with bottom elevations of 559 feet, well below the tailwater elevation, and are controlled with drop gates with three leaves. The 19 center gates have shallow sills with bottom elevations of 581.5 feet, slightly above normal tailwater elevation, and are controlled with two drop gate leaves. Gates 21-23 discharge to a very shallow concrete step. Nine gates have been retrofitted with notched upper leaves to optimize downstream fish passage. Historically the Columbia River has overtopped the dam during extreme floods.

The bathymetry of the tailwater channel is highly variable, and is composed of a complex array of spires, channels, and holes. Bottom elevations vary from 568 feet downstream of Bay 7 to a deep hole below Bay 30 with an elevation of less than 500 feet. A shallower channel below bays 5-23 range in elevation from 550-560 feet, while a deeper channel at the east and west ends of the spillway range from 530-540 feet. The river bed continues to be fairly complex until about 200 feet downstream.

TDG Generation Processes

Chelan PUD did a limited assessment of TDG production during in the 1999 season (Perleberg and McDonald, 1999). A moderate to strong relationship was found between the increase in TDG from forebay to tailrace at Rock Island Dam and spill volumes, both as total discharge and percent of river flow. The change in TDG from forebay to tailrace averaged around 6% saturation with maximum increases of 15 to 17% saturation. Transect measurements showed a slight trend towards decreasing TDG levels laterally from east to west across the channel.

An intensive TDG investigation was conducted at Rock Island Dam on June 17-22, 1999 (Schneider and Carroll, 1999). Meters were placed in transects in the forebay, immediately downstream of the spillways, about 600 feet downstream of the dam, and adjacent to the tailwater fixed monitoring station about 6,000 feet downstream. Twelve spill events with varying volumes and patterns were scheduled, with total spillway discharges ranging from 11.0 to 94.4 kcfs. Unit spillway releases ranged from 1.7 to 40.3 kcfs per bay. Spill patterns varied widely, and included use of the notched weir, overflow discharge, and discharge under the gates; and use of deep sill gates, shallow sill gates, and the gates with concrete pads.

Results suggested that forebay TDG levels are transferred unchanged through the powerhouses, which is typical of other Columbia and Snake River dams. Spills to the concrete pad were observed to actually reduce forebay gas levels, but only at low total spill levels. Transect 2, located 600 feet below the spillway, measured the highest TDG levels with a maximum level of 137.5% saturation. Average TDG pressures downstream were found to be a linear relationship to total spillway discharge, which is a similar finding to the results of earlier studies.

Overall, underflow releases in deep spill bays showed the most promise for the lowest TDG generation. However, existing equipment is inadequate to pull all three leaves of most deep sill gates, so an upgrading of equipment would be necessary. Under standard spills (overflow), use of shallow sill gates produced the lowest TDG levels. For low unit spill discharges the concrete bays also produced low TDG levels. Use of the deep spill bays for overflow spill releases produce higher TDG levels, and likely also entrain powerhouse flows producing higher levels of TDG loading. The notched fish passage gates tended to produce the highest levels of TDG, but the low spills associated with fish passage allowed lower TDG levels downstream due to dilution from powerhouse flows.

The representativeness of TDG readings at the tailwater fixed monitoring station can vary according to spillway and powerhouse operations. Spill flows tend to hug the east bank, and the river is not fully mixed at the tailwater FMS. Operation of the Second Powerhouse will tend to push higher TDG flows into the east bank. However, First Powerhouse flows can have the opposite effect, pushing higher TDG flows towards the middle of the channel so that FMS readings reflect forebay TDG levels carried by powerhouse flows.

In September 2000, Chelan PUD installed a prototype flow deflector at Bay 29, a deep sill spill way at the west end of the spillway. An angled deflector was built on the endsill below the spillway to redirect spill flow slightly upward. Bay 29 is operated as a notched overflow weir for fish passage. The Corp conducted an evaluation of the deflector's TDG performance (Carroll et al., 2001). Pre- and post-deflector monitoring surveys were conducted below Bays 29 and 30 (the bay next to 29 used as a control). The study found comparable TDG levels below both bays during pre-deflector monitoring. Post-deflector monitoring found an average reduction in TDG of 4.5% saturation below Bay 29. The complexities introduced by the variability of river flow, tailrace elevation, powerhouse flows, upstream TDG levels, spill discharge rates, and spill pattern makes it difficult to extrapolate results to a wider range of conditions

In 2001, Chelan PUD had the Corps test a prototype defector below Bay 16 for use with a notched weir overflow spill for fish passage (Carroll et al., 2002). Bay 16, a shallow bay with a flat concrete pad, was retrofitted with an angled deflector on the endsill to redirect spill flow slightly upward. The study paired Bay 16 with Bay 18, and monitoring was conducted before and after deflector installation. Despite extremely low flows that limited the ability to spill, the study was able to show reductions in TDG saturation from the deflector by as much as 6% saturation. TDG levels during this study never exceeded 110% saturation. As with the previous single-bay study, it is difficult to extrapolate these results to a wider range of conditions.

6. Wanapum Dam

Project Description

Wanapum Dam (Figure D-6) is owned and operated by Grant Public Utility District, and is located downstream of Vantage. The project information below is summarized from Grant PUD's April 2003 draft License Application for FERC relicensing (Grant PUD, 2003).

The normal pool operating range is between 560 and 571.5 feet elevation. The entire structure is 8,637 feet, about two-thirds of which is embankment. The powerhouse and spillway are bent at an angle away from each other; the powerhouse is 1,000 feet long on a roughly north-south orientation, while the spillway runs is 832 feet from the northeast to southwest. Fish ladders and space for future powerhouse units make up the balance of the structure.

The powerhouse contains 10 turbine units which operate at a design head of 80 feet and discharge of 163 kcfs. The spillway has a total design capacity of 1,400 kcfs, and includes 12 tainter gates, each 50 feet wide, and a 20 foot wide top-spilling sluice gate at the east end of the spillway. The 12 spillways have been retrofitted with deflectors for TDG abatement. Energy dissipation is provided by stilling basin, which consists of a level concrete apron extending 80 feet downstream.

TDG Generation Processes

Wanapum Dam has gone through an extensive program of gas abatement. Several prototype spill deflectors were designed, installed in single bays, and tested in the late 1990's. In early 2000, spill deflectors were installed in all 12 spill bays. Installation of spill deflectors at Wanapum Dam has significantly reduced TDG generation by spill.

Post-deflector testing was conducted by the Corps in spring 2000 (USACE, 2001c). Thirty meters were placed in five locations: in the forebays of Wanapum and Priest Rapids dams; and three transects 800 feet, 2100 feet, and 16,000 feet downstream of the spillway. The downstream transect was located near the tailwater fixed monitoring station at the Beverly Railroad Bridge.

River flows during the study varied between 142 and 268 kcfs, resulting in tail water elevations ranging from 492 to 497 feet. The dam used a variety of powerhouse flows and spill volumes and patterns during the study. Powerhouse flows were used to vary tailwater elevations. Spill patterns included uniform spill, fish migration spill, and fish spill with the sluice gate closed. The uniform pattern discharges relatively evenly from all bays, while the fish spill usually has higher spill from one to eight bays at the west end of the spillway. Spill volumes varied from 3.7 to 12 kcfs per bay.

The highest TDG pressures during the study were measured along Transect 1, closest to the center of the spillway. The highest value observed was 136.5% saturation during a uniform spill event of 12 kcfs per bay (the highest spill in the study). TDG levels from meters at the east end of Transect 1 were strongly affected by powerhouse flow and resembled forebay levels.

Transect 2 (2100 feet downstream) measured conditions below the turbulent aerated zone, and reflected a mix of spillway and powerhouse TDG conditions. The highest TDG levels were found near the west (spillway) side of the channel, with maximum TDG measured at 129.3% saturation during maximum spill. Twice when spillway discharges were below 50 kcfs, downstream TDG levels were observed to drop below forebay TDG levels. This suggests that some degassing or stripping of TDG is occurring under these conditions.

Transect 3, about 3 miles downstream from Wanapum Dam near the fixed monitoring station, continued to show lateral variation with higher TDG levels near the west bank. The maximum TDG observed at this transect was 124.9% saturation, again during the maximum spill. Some stations on the east end of the transect showed evidence of degassing under certain conditions, which may be related to a shallow channel section near the east bank. The fixed monitoring station tended to measure a mid-range of TDG levels, with lower levels than meters to the west, but higher levels than meters to the east.

Lateral gradients continued to be observed in the Priest Rapids Dam forebay, with levels again increasing from east to west. Conditions at the forebay fixed monitoring station (located in the center of the dam) were variable, with levels sometimes higher and sometimes lower than either side of the channel. In general the effects of spill releases from Wanapum Dam translated themselves downstream with some mixing and attenuation of peaks.

Pre-deflector and post-deflector TDG levels were compared to evaluate reductions in TDG due to the deflectors. Looking at the higher values on the west side of the channel, deflectors reduced TDG levels by approximately 11% saturation. TDG levels averaged over the cross section showed greater reductions for low river flows than for high river flows, with reductions of 3-4% saturation at flows of 60 kcfs or less and 1-2% at flows of 100 kcfs or more. A 7Q10 spill flow of 118 kcfs produced 128% saturation, which is a significant reduction from TDG levels of over 140% prior to deflector installation.

Spills of up to 85 kcfs are expected to remain below the tailwater fish passage TDG criteria of 120% saturation, as compared to a spill of 20 kcfs having this effect prior to deflector installation. Spills up to 60 kcfs should meet the Priest Rapids forebay TDG criterion of 115% saturation, as compared to the pre-deflector spill limit of 16 kcfs at this location.

TDG generation was found to be a linear function of unit spillway discharge. The study found a weak relationship of TDG levels to tailwater elevation, with data suggesting that TDG levels are slight lower as tailwater levels rise. This result is contrary to what is usually observed at Columbia River dams.

Velocity measurement in the Wanapum Dam tailrace indicated flows moving from the powerhouse discharge into the spill. This suggested that powerhouse flows were being entrained into the spill and being aerated along with the spill. A mass balance calculation comparing TDG levels below the spillway to the average TDG levels at Transect 3 pointed towards significant entrainment of powerhouse flows under certain conditions. The calculations estimated that a partition wall to separate powerhouse flows from the aerated spill could reduce average downstream TDG levels by 1-2% saturation.

7. Priest Rapids Dam

Project Description

Priest Rapids Dam is owned and operated by Grant Public Utility District, and is located upstream of the Vernita bridge (Figure D-7). The project information below is summarized from Grant PUD's April 2003 draft License Application for FERC relicensing (Grant PUD, 2003). Priest Rapids Dam is the last dam on the Mid-Columbia River before the river enters the Hanford Reach and eventually meets the Snake River.

The normal pool operating range is between 481.5 and 488 feet elevation. The entire structure is 10,103 feet long, of which 7,385 feet are rock-filled embankment, and runs straight across the channel perpendicular to river flow. The powerhouse is 1,025 feet long and contains 10 turbine units which operate at a design head of about 80 feet and discharge of 165 kcfs. The spillway is 1,152 feet long with a total design capacity of 1,400 kcfs. The spillway consists of 22 tainter gates, each 40 feet wide.

Energy dissipation is provided by stilling basin, which consists of a level concrete apron extending 75 feet downstream at 387 feet elevation with a sloped end sill rising to 391 feet. Tailwater elevations are typically between 400 and 412 feet, resulting in stilling basin depths of 13-25 feet.

Downstream of the stilling basin, bottom elevations range from 390 to 404 feet. Areas shallower than 400 feet can become exposed when tailwater elevations are low. The river as it enters the free-flowing Hanford Reach moves through areas with shallow areas and islands, with deeper areas over 35 feet in depth.

TDG Generation Processes

An intensive study was conducted between July 21 and August 4, 2003 to characterize TDG production by spill at Priest Rapids Dam and transport into the Hanford Reach (USACE, 2003). Total river flow was held constant and standard spill varied over four spill discharge rates (from 27 to 100 kcfs), at two powerhouse flow rates (50 and 150 kcfs), and at constant total flow (150 kcfs) with variable powerhouse flows. A spill of 100 kcfs combined with a powerhouse flow of 150 kcfs approximates conditions just below a 7Q10 flood flow. Non-standard spill was also tested by spilling from only the west, central, and east sections of the spillway. Each test treatment was scheduled to last at least 3 hours, to allow conditions to equilibrate.

Twenty-one meters were placed above and below the dam to evaluate TDG conditions. A transect of four meters were placed in the forebay; six meters were placed directly below the dam – four below the spillways, one at the powerhouse draft tube deck, and one at the entrance to the north fish ladder; a transect of six meters was placed at the USGS flow gaging station a couple miles downstream; and a transect of five meters were placed at the Vernita Bridge, which is also the site of the fixed monitoring station.

The highest TDG levels during the study were measured just below the spillway and reached over 135% saturation. In general TDG levels below the spillway were proportional to total spill (although the highest spill did not produce the highest TDG levels). During the lowest spill levels (specific discharges of less than 2 kcfs/bay), TDG levels below the spillway dropped from forebay levels, suggesting that the spill was causing degassing. Where the specific spill discharge varied between bays, higher TDG was seen below bays with higher specific spills.

TDG was also proportional to tailwater elevations. TDG could be observed to rise and fall with tailwater elevation changes. Under one pair of spill events, when spill increased but the tailwater elevation decreased, TDG production decreased as well.

Spillway bays near the powerhouse showed evidence of dilution with powerhouse flows. Bay 22, which discharged with a fully aerated top spill during the entire study, tended to generate higher TDG levels than the other bays for the same specific discharge rates.

Lateral gradients in TDG were observed downstream at both the USGS and Vernita Bridge transects, corresponding to spillway and powerhouse flows. The fixed monitoring station at Vernita is midchannel, and tended to represent relatively high TDG levels, but the right bank study monitor usually showed higher TDG levels than the FMS.

Transect values were averaged and compared for forebay, spillway, and downstream. From the forebay to the USGS site, the change in average TDG ranged from a decrease of 1.1% saturation to an increase of 10.6% saturation. The average change over the study was 2.3% saturation.

During the highest river flows and spills (145 kcfs spill at 272 kcfs flow), average TDG reached its highest level of 129.4% below the spillway, 122.2% at the USGS transect, and 121.5% at the Vernita Bridge. Decreasing TDG at these flow levels was mostly due to mixing of powerhouse flows with lower TDG levels from the forebay. However, some degassing occurred, especially between the USGS and Vernita sites. This effect was increased by higher wind velocities and shallower flow, which would be expected.

A non-linear regression was used to develop an equation to predict average TDG below the spillway. A good prediction was developed for TDG as a linear function of tailwater depth and an exponential function of specific discharge. TDG exchange tends to be controlled by the specific discharge at low levels of discharge, but at high specific discharges the tailwater depth becomes the dominant factor.

Using the non-linear regression and a simple mass-balance mixing model, TDG levels at the USGS transect were predicted from specific discharge, tailwater elevations, average forebay TDG, and powerhouse flows. A good prediction was obtained, which indicates that entrainment of powerhouse flows into the aerated spill is negligible. The training wall between the powerhouse and stilling basin reduces the interaction of these flows.

Loading Capacity

Linkage of TDG Loading to the Criteria

As discussed above, the fundamental process that elevates TDG is gas transfer between the air and water at the boundary of entrained bubbles, driven by differential gas pressures. For any given spill volume and tailwater depth, the excess pressure over ambient barometric pressure, ΔP, can be predicted. The mass loading of air that is associated with any given ΔP will depend on water temperature. However, this mass loading is of less importance than ΔP, since it is ΔP that drives whether gas bubble trauma will occur. For these reasons, using excess pressure rather than mass loading to express loading capacity is appropriate for this TMDL, and is supported by the Clean Water Act's allowance for the use of "other appropriate measures" in the development of TMDLs.

To determine the TMDL loading capacity, ΔP can be directly related to the TDG water quality criteria, as described in Equation 6:

$$S_{tdg} = \frac{(P_{atm} + \Delta P)}{P_{atm}} * 100$$

If S_{tdg} is set at the criterion of 110% saturation, the equation can be rearranged to establish a ΔP loading capacity (ΔP_{lc}):

$$\Delta P_{lc} = P_{atm} * 0.1$$

To choose a critical barometric pressure P_{atm} for establishing a loading capacity, the 95th percentile low pressure was determined during the spring and summer spill season. This pressure varies from 748 mm Hg at the downstream boundary above the Snake River to 721 mm Hg in Lake Roosevelt. Therefore, loading capacities for the Mid-Columbia River and Lake Roosevelt are set to the values of ΔP shown in Table 4.

The use of critical barometric pressure to set a value of ΔP to meet the criterion of 110% saturation is appropriate because of the need to meet the criteria throughout the river as conditions change downstream of the dams and away from compliance locations. However, the TDG criteria for fish passage are very specific for their location of application and are silent about the required levels away from the compliance locations. Therefore, loading capacities for fish passage will be set in terms of percent saturation, and are equal to the criteria.

Table 4: Loading Capacities for the Mid-Columbia River and Lake Roosevelt

Reach of Columbia River	Loading Capacity
Lake Roosevelt (all conditions)	72 mm Hg above saturation (ΔP)[1]
Grand Coulee Dam to Okanogan River (all conditions)	73 mm Hg above saturation (ΔP)[1]
Non-fish passage – Okanogan River to Wells Dam	73 mm Hg above saturation (ΔP)[1]
Fish passage – Forebays of Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids dams[2]	115 % Saturation[3]
Fish passage – Tailrace Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids dams [2]	120 % Saturation[3]
Fish passage – Tailrace of Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids dams [2]	125 % Saturation[4]
Non-fish passage - Wells Dam to Yakima River	74 mm Hg above saturation (ΔP)[1]
Yakima River to Snake River (all conditions)	75 mm Hg above saturation (ΔP)[1]

[1]maximum instantaneous
[2]when authorized by Ecology after approval of a gas abatement plan
[3]average of 12 hourly readings in a 24-hour period
[4]maximum hourly reading

Load Allocations

For the purpose of this TMDL, each dam will be provided with a load allocation, because no NPDES permits will be issued to the dams to regulate TDG caused by spills[1]. This approach is also reasonable for several reasons:

- Spills entrain air to reach a polluted state, much like a high-energy release of water might erode a stream bank.
- Dams are essentially very large instream structures that will require modifications to achieve attainment of water quality standards.
- The level of improvement expected from any specific structural or operational modification is uncertain, and therefore a series of modifications may be needed to achieve the desired outcome, with effectiveness monitoring to assess results.

Wasteload allocations in this TMDL are zero, because there are no NPDES-permitted point sources that contribute to elevated TDG in the Mid-Columbia River or Lake Roosevelt.

Table 5 shows the load allocations for forebays and tailraces of each of the seven dams on the Mid-Columbia River, the international boundary and the Spokane River inflow. As noted previously, because of the unique nature of TDG, load allocations are not directly expressed in terms of mass loading. Spills are independent of upstream conditions. Each dam's spill "resets" the TDG levels for the water that passes over the spillway and for any entrained powerhouse water. Tailrace allocations are met below the spillway where conditions are entirely or predominantly representative of the spill.

Downstream levels are a simple mass balance of each dam's TDG generation from spill plus powerhouse flows that pass forebay levels from upstream. Therefore for non-fish passage, if TDG comes from Canada at 110%, and each dam doesn't increase the gas in it's spill above 110%, the river will always meet 110%.

Like loading capacity, allocations are in terms of percent saturation for fish passage and in terms of ΔP at all other times and locations. Load allocations are equal to loading capacity throughout the TMDL area, including each dam’s forebay and tailrace. The load allocation for the downstream boundary above the Snake River is also equal to the allocation at the upstream boundary of the Lower Columbia River TDG TMDL (Pickett and Harding, 2002).

[1] The Courts have determined the characterization of dams as point sources for which NPDES permits will not be issued for certain parameters. The current policies of the state of Washington and EPA are to not issue NPDES permits for TDG.

Table 5: Load Allocations for TDG in the Mid-Columbia River

Reach of Columbia River	Load Allocation
All Conditions - Lake Roosevelt, including Spokane Arm and Grand Coulee Dam forebay	72 mm Hg above saturation[1]
All Conditions - Grand Coulee Dam to Okanogan River	73 mm Hg above saturation[1]
Fish passage – Forebays of Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids dams[2]	115 % Saturation[3,5]
Fish passage – Tailrace Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids dams[2]	120 % Saturation[3,5]
Fish passage – Tailrace of Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids dams; Hanford Reach to the Snake River[2]	125 % Saturation[4]
Non-fish passage – Okanogan River to Wells Dam	73 mm Hg above saturation[1]
Non-fish passage – Wells Dam to Yakima River	74 mm Hg above saturation[1,6]
Non-fish passage - Yakima River to Snake River	75 mm Hg above saturation[1]

[1]maximum instantaneous
[2]when authorized by Ecology after approval of a gas abatement plan; allocations only apply if spill is occurring
[3]average of 12 hourly readings in a 24-hour period
[4]maximum hourly reading
[5]For each dam, if upstream forebay levels exceeding the load allocation make it impossible to meet the load allocation for the forebay of the next downstream dam, then the tailrace load allocation will be 115% and the allocation for the forebay of the downstream dam will not be in effect.
[6]For Wells Dam, if upstream forebay levels exceed the load allocation, then TDG levels in the downstream compliance area shall not exceed upstream forebay levels.

Long-term Attainment of Water Quality Standards

Attainment of Standards for All Spills

Federal and state laws and rules require attainment of state water quality standards, and therefore the ultimate goal of this TMDL is to achieve attainment. Special criteria have been established in Washington for "voluntary" spills for fish passage, and this TMDL includes allocations for that situation.

For a dam wholly within Washington's jurisdiction to be covered by the allocations for fish passage, Ecology must designate the fish passage period (beginning and ending dates) based on the recommendations of NOAA Fisheries and other decision-making bodies, and must approve the gas abatement plan for the dam. Spills in support of fish passage (such as for research or performance testing) can also be included by the fish passage load allocations with prior approval from Ecology.

Spills can occur at any time and at any volume due to lack of power demand or powerhouse maintenance or failure. Therefore, this TMDL will be applicable for all spills below 7Q10 river flood flow conditions, regardless of the cause of the spill. Table 6 shows the estimated effect on TDG levels, if a spill at a rate equivalent to the 7Q10 flow were to occur.

Table 6: Predicted TDG for 7Q10 Spill

Dam	7Q10 (kcfs)	100% spill *TDG (%sat)*	50% spill *TDG (%sat)*	7Q10 less 90%PH (kcfs)	%spill	*TDG (%sat)*
Grand Coulee	222	*154*	*154*	0	0%	*0*
Chief Joseph	222	*145*	*137*	25	11%	*122*
Wells	246	*142*	*126*	48	20%	*116*
Rocky Reach	252	*150*	*131*	54	21%	*120*
Rock Island	264	*145*	*128*	66	25%	*119*
Wanapum	264	*149*	*129*	117	44%	*126*
Priest Rapids	264	*129*	*129*	116	44%	*129*

Operational versus Structural Solutions

The Mid-Columbia River dams, as currently designed, will not be able to meet TDG criteria for all spill flow levels up to the 7Q10 flow. Table 6 illustrates three cases: a spill of the entire river at 7Q10 flow, a 50% spill at 7Q10 flow, and a spill at 7Q10 flow if 90% of powerhouse capacity is available. TDG is estimated from regression equations developed for these dams using data from fixed monitoring stations or special studies. None of the dams will likely meet even the 125% TDG criterion if forced to spill the entire river at 7Q10 flows. However, most of the dams can meet the 120% criterion if they are able to use most of their powerhouse capacity. With the addition of flow deflectors and/or additional powerhouse capacity at several projects, it is likely that all dams could at least achieve 120% saturation.

Therefore, attainment of this TMDL's allocations may include structural changes. The Summary Implementation Strategy (Appendix A) outlines a variety of alternatives for operational and structural changes, which move in the direction of compliance under all spill levels. However, the effectiveness of these changes can only be estimated, and must be assessed after implementation. Also, implementation of structural solutions is dependent on Congressional appropriations or the financing and budgeting limitations of the Public Utility Districts. Therefore long-term attainment of allocation set in this TMDL will take a significant length of time and must take into account a certain level of inherent uncertainty.

In addition, compliance with standards, especially with the 110% criterion where and when applicable, will depend on operational solutions. Management of river flows and spill patterns can help minimize spill. Also, the ability to fully utilize powerhouse capacity during high flows could help reduce periods when TDG criteria are exceeded, but this would depend on developing additional power use and marketing strategies. Development and implementation of operational tools to minimize TDG generation is an on-going process, and further research is likely to produce additional improvements.

Compliance Areas

In this TMDL, the geographic area where the TMDL is in effect is termed the "compliance area". Monitoring for TMDL compliance will occur at locations within or near the compliance area, as described in the Summary Implementation Strategy and in future implementation and monitoring plans.

The pools behind each dam, and the reach from Priest Rapids dam to the Snake River, will each have compliance areas defined, for a total of eight compliance areas in this TMDL. From Grand Coulee to Priest Rapids dams the compliance areas will extend from the tailrace of the upstream dam to the forebay of the downstream dam. The compliance area of Lake Roosevelt will extend from the Canadian border to the forebay of the dam. The compliance area downstream of Priest Rapids Dam extends from the tailrace to the confluence of the Snake River.

Load allocations for non-fish passage conditions below the Okanogan River, and under all conditions above the Okanogan River, have to be met at all locations throughout each compliance area. Load allocations for fish passage are specified for each tailrace, forebay and for the Hanford Reach, and have to be met at the fixed monitoring station locations established at the upstream and downstream boundaries of the compliance areas.

The tailrace compliance area boundaries for the dams were chosen from several options, illustrated in Figure 14:

1. By a strict interpretation of state water quality standards without any consideration of applying the mixing zone provisions of the water quality standards, the tailrace compliance area would be the entire river from the dam downstream. This includes the area of maximum TDG immediately below the spillway. However, this area is difficult to identify and monitor in real time, and does not take into account the rapid degassing in the aerated zone.

2. If mixing zone provisions were applied to the aerated zone (the area of bubble entrainment and dissipation), then the tailrace compliance area would begin at the end of the aerated zone. This location would be easier to identify for regulatory purposes.

3. The area of compliance could begin at the tailwater FMS sites, but mixing zone provisions would need to be applied to the entire river, including powerhouse flow. The locations of the tailwater FMS sites are clearly identified. However, they are inconsistent with respect to the amount of mixing they represent between water gassed by the spill and water unchanged from the forebay.

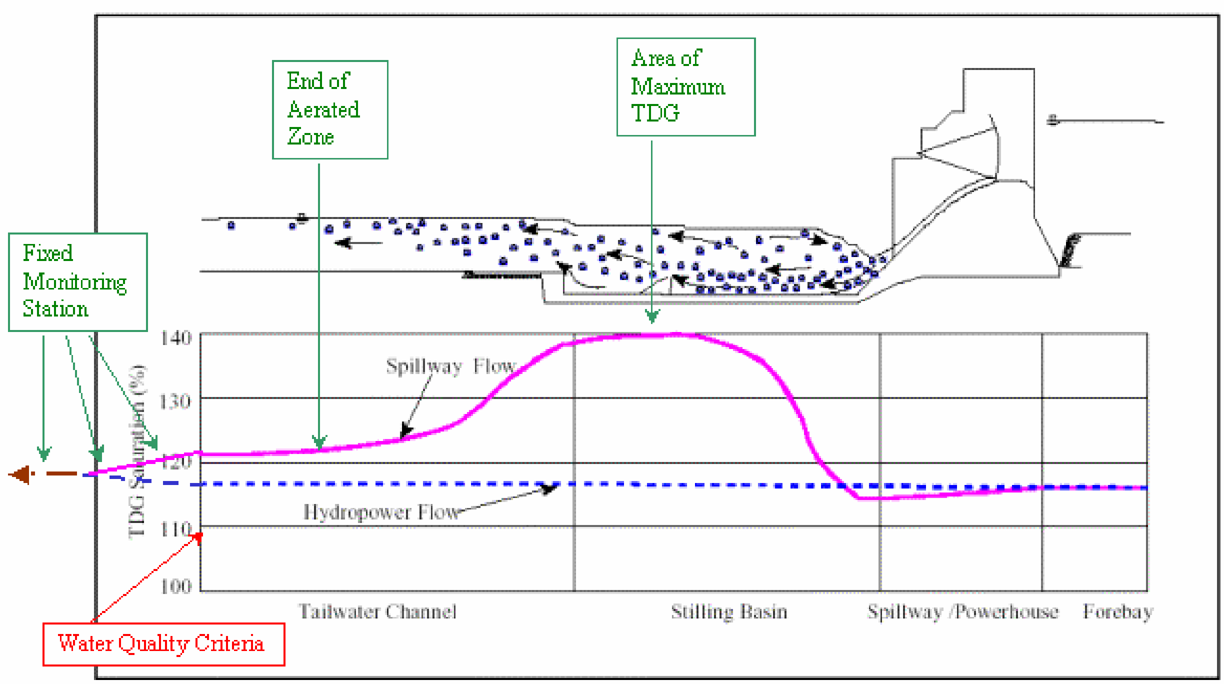

Figure 14: Key Features of Potential Tailwater Compliance Area Boundaries.

The upstream boundaries of the compliance areas above the Okanogan River will extend to the base of Chief Joseph and Grand Coulee dams. The upstream boundaries of tailwater compliance areas below the Okanogan River will be based on application of the mixing zone to the aerated zone immediately below the spillways of the Mid-Columbia dams. The water quality standards for the state of Washington provide an allowance for a mixing zone, and compliance with standards is required at the boundary of the mixing zone. There are several reasons that use of a mixing zone is appropriate in this situation:

- TDG levels rise immediately below the spillway, but then degas for some distance downstream. The tailrace compliance area boundaries were determined from field observations or research which identified the location where degassing was mostly complete. This is a local area of impact with very dynamic conditions.
- Because the area below the spillway is very dynamic, TDG levels are difficult to accurately assess.
- Extensive fisheries research has shown that most anadromous fish are able to pass through this area below the spillway quickly without ill effects.
- Because of the turbulent flow associated with the spill above the compensation depth (the depth where hydrostatic pressure equals ΔP), little or no resident fish habitat is available in this area. (The zone below the compensation depth is by definition in compliance with standards.)

- Provision of a mixing zone and deviation from the size requirements are appropriate because of the public interest in ensuring that water quality standards are applied appropriately to the dam projects.

The upstream boundaries of compliance areas are shown in Table 7. The tailrace compliance areas for tailrace load allocations will begin at the end of the spillway for Grand Coulee and Chief Joseph dams, and at the end of the aeration zone in the tailrace of other dams, at the locations specified in the Table 7. Each dam will be responsible for managing its own spill to remain in compliance with the standards, but will not be responsible for high TDG levels produced upstream and passed through the powerhouse.

Table 7: TMDL Compliance Area Upstream Boundaries

Project	Location
Upstream Boundary	Lake Roosevelt below Canadian Border
Spokane Arm Boundary	Lake Roosevelt below Little Falls Dam
Grand Coulee Dam tailrace	end of spillway
Chief Joseph Dam tailrace	end of spillway
Wells Dam tailrace	2000 feet below end of spillway [1]
Rocky Reach Dam tailrace	1600 feet below end of spillway [2]
Rock Island Dam tailrace	2000 feet below end of spillway [3]
Wanapum Dam tailrace	2000 feet below end of spillway [4]
Priest Rapids Dam tailrace	1500 feet below end of spillway [5]

[1]Pickett, 2002
[2] USACE, 2003a
[3] Schneider and Carroll, 1999
[4] USACE, 2001c
[5] USACE, 2003

Monitoring of Attainment

For monitoring of long-term attainment, it will be necessary to monitor throughout the load allocation compliance areas, and especially at the boundaries. However, it is not expected that these locations will lend themselves to a permanent remote monitoring setup. Attainment of the allocations will be determined in two ways: (1) periodic synoptic surveys, especially after structural changes have been completed, and (2) continuous monitoring, using a statistical relationship between the continuous monitor and conditions at the designated monitoring location. This allows long-term monitoring to be managed separately from monitoring for short-term operational needs.

For short-term targets, the FMS stations can continue to be used, or new FMS stations can be established. This will allow operational management that is linked to easily accessible data, based on overall environmental management needs and the realities imposed by structural characteristics. Thus, short-term targets can remain adaptive and flexible, while long-term targets remain fixed to firm goals.

Compliance with fish passage allocations will be assessed at the fixed monitoring stations. Ideally fixed monitoring stations will be sited to assess the location where the highest time-averaged TDG values can be found.

Compliance with allocations in the pools under non-fish passage conditions will be assessed both by comparison of FMS tailrace and downstream forebay monitoring, and by detailed synoptic surveys. Detailed monitoring may be appropriate following changes in temperature management procedures that alter typical temperature increases, such as through implementation of a temperature TMDL or ESA requirements.

Margin of Safety

The margin of safety for this TMDL is implicit in the TMDL analysis through the use of conservative assumptions. A detailed analysis of how the margin of safety is included is provided below.

Critical Conditions

No specific high- or low-flow critical conditions exist for this TMDL. Spills that generate high gas levels can occur in any season and load allocations are applicable to spills at all flow levels below the 7Q10 flood flow.

Certain parameters that are necessary to develop load allocations were established at levels equivalent to critical conditions. As described above, time of travel, temperature, and barometric pressure were all developed at critical levels. This approach introduces several conservative assumptions that provide a margin of safety to the TMDL.

Criteria versus Site-specific Conditions

Probably few river systems have been as extensively studied for the effects of TDG than the Columbia system. Extensive research has been conducted for over 40 years on TDG and aquatic life. Currently federal, state, and tribal fishery agencies all support a more lenient standard than currently in state regulation. Review of EPA guidance also suggests the criterion could be applied with an averaging period, rather than as an instantaneous value. Therefore, the current standards include an implicit margin of safety when applied to this river system.

Data Quality and Quantity

A margin of safety is usually identified in a TMDL to recognize uncertainty in the data used to produce the TMDL. Due to the monitoring requirements imposed by the Washington State Department of Ecology as a part of the fish passage program over the past seven years, there is a great deal of hourly data of TDG levels, barometric pressure, water temperature, tailwater elevation, forebay elevation, total river flow and spill quantity. Fairly rigorous standardized data quality procedures are provide for these data. These data are available on the Technical Management Team homepage, hosted by the Northwest Division of the U.S. Army Corps of Engineers at: http://www.nwd-wc.usace.army.mil/TMT/welcome.html.

Seasonal Variations

TDG levels above 110% saturation historically occur most commonly during mid-April to the end of August, which is both the fish migration season and the high-flow season in conjunction with spring runoff. One of the determinants of TDG levels is total river flow. When river levels are particularly high, TDG levels rise more rapidly if there is any water spilled over the spillway. During low-flow periods, there is generally not a TDG problem, other than spill for fish passage, as long as all water is passed through the powerhouses.

Occasionally turbine units will be out of service for maintenance, either scheduled, or on an emergency basis. This may require water to be spilled, because there are insufficient turbines available to handle the water in the river. This can occur due to Bonneville Power Administration power purchasing and the sequencing of water releases from upstream storage reservoirs.

Clearly, there is little control over emergency outages. Maintenance is generally scheduled (1) to coincide with low electricity demand periods, and (2) when river flows are such that they will not cause TDG exceedances.

In summary, spills can occur at any time, although they are most likely in the spring and early summer. The TMDL has been written so that the limits apply at any season, since they are based on spill and not on river conditions. The *Margin of Safety* section describes how seasonal critical conditions were applied to the development of load allocations. TMDL limits apply year-round, but they have taken season critical conditions into consideration.

7Q10 Flows

As discussed above, Washington's and the Colville Tribe's water quality standards only apply when river flows are below the 7Q10 flood flows and the proposed Spokane Tribe's water quality standards do apply for these flows. These flows, shown in Table 8, were calculated from flows measured and reported by the U.S. Geological Survey. Methodology followed the guidelines of the U.S. Water Resources Council (1981):

Table 8: Lake Roosevelt and Mid-Columbia River 7Q10 Flood Flows

Reach	Flow (kcfs)
International Border to upstream end of Lake Roosevelt	227
Spokane Arm of Lake Roosevelt	33.4
Lake Roosevelt to Okanogan River (Grand Coulee and Chief Joseph dams)	222
Okanogan River to Chelan River (Wells Dam)	246
Chelan River to Wenatchee River (Rocky Reach Dam)	252
Wenatchee River to Snake River (Rock Island, Wanapum, and Priest Rapids dams)	264

Annual peak 7-day average flows were calculated (using the October-September Water Year from 1975 through 2000), and then the 10-year return flow was determined by the Log-Pearson Type 3 method. The skew coefficient used in the analysis was calculated from the data; the generalized and weighted skew was not determined or used, but the error introduced by this shortcut was probably small to nil.

USGS flow gaging stations were evaluated by comparison to upstream or downstream stations, while adding or subtracting major tributaries. Several stations appear to have unreliable flow measurements at high flows. Discussions with USGS staff indicated that several factors appear to introduce this error: backwater from downstream pools (for instream measurements); and errors in estimating flow through the spillways (for measurements taken at dams). The USGS gages at Priest Rapids, Wells Dam, Bridgewater, and the International Border appeared to provide the most reliable data, and were used as the basis for determining 7Q10.

Summary of Public Involvement

The state of Washington and the Spokane Tribe developed and implemented the Public Involvement and Outreach strategy for this TMDL project in partnership with the Columbia/Snake Rivers Mainstem TMDL Coordination Team. These TMDL team members include the U.S. Environmental Protection Agency, Spokane Tribe, Washington State Department of Ecology, Columbia Basin Tribes, and the Columbia River Inter-Tribal Fish Commission.

The public comment period on this proposed TMDL began ______ and ended ______.

Public hearings were held:

- ______

Individual outreach meetings were held with the appropriate watershed advisory groups and with primary stakeholders, which included:

- Spokane Tribe
- Confederated Tribes of the Colvilles
- U.S. Army Corps of Engineers (Portland, Walla Walla, and Seattle Districts, and Pacific Northwest Division)
- Grant, Chelan, and Douglas Public Utility Districts
- U.S. Bureau of Reclamation
- Bonneville Power Administration
- NOAA Fisheries

In addition, meetings and presentations were held with the NOAA Fisheries Water Quality Team that includes federal and state agencies, public utility agencies, tribes, and Bonneville Power Administration.

The TMDL team held public meetings to receive input and comments from all interested participants. These meetings included public workshops to accept informal comments for each regional phase of the TMDL project, and public hearings for the formal public comment period.

The TMDL team used public outreach tools such as letters, focus sheets, and other printed materials; websites with short narratives and graphics, downloadable documents and relevant links; news releases and special news articles; and field visits.

Public Involvement Actions

- U.S. Environmental Protection Agency and Department of Ecology websites
- Focus sheets

- News releases
- Periodic coordination team meetings – EPA, Idaho Department of Environmental Quality, Oregon Department of Environmental Quality, Washington State Department of Ecology, Columbia Basin Tribes, Columbia River Inter-Tribal Fish Commission (CRITFC), and other stakeholders.
- Periodic conference calls with Ecology, EPA, Spokane Tribe, Colville Tribe
- Monthly updates and discussions with the NOAA Fisheries Water Quality Team
- Presentations to the NOAA Fisheries Implementation Team
- Periodic meetings with Transboundary Gas Group

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Appendices:

(Appendices A, C, D, and E. are separate files linked to this report on the web.)